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Workshop on Exploration for Hot-Dry-Rock Geothermal Systems

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WORKSHOP ON EXPLORATION FOR HOT-DRY-ROCK GEOTHERMAL SYSTEMS

Compiled by

G. H. Heiken, M. E. Ander, and T. J. Shankland

ABSTRACT

Most of the world's geothermal resources are not present in the form of active hydrothermal systems but as hot dry rock (HDR). HDR makes up by far the largest fraction of geothermal regions, but natural fluids are absent and water must be introduced artificially for production of steam or hot water. Recognizing the huge thermal resource available, several countries now have HDR experiments. HDR resources lack the sharp physical and chemical contrasts produced by geysers and hot springs and thus present unusual exploration problems. Exploration for HDR was the subject of a workshop held in Los Alamos, New Mexico, 21-23 June, 1982.

It was apparent that many aspects of HDR exploration comprise basic crustal studies, including continental scientific drilling. Thus, virtually all speakers emphasized a multidisciplinary approach to exploration. The most useful data are obtained from careful measurement of heat flow. Heat flow data may be linked, and the extent of regional thermal anomalies determined, through the use of magnetotelluric surveys and depth-to-Curie point mapping. In particular, there is strong evidence for a correlation between depth to deep crustal electrical conductors and surface heat flow. Gravity data have been used to locate HDR anomalies associated with favorable buried silicic and alkalic intrusive bodies.

A variety of seismic methods can help identify the thermal anomalies, structural features, and depth to potential reservoir rocks in areas with a HDR resource. Geological surveys provide a framework within which data from the geophysical surveys may be interpreted; they also include petrologic, structural, and temporal studies of heat sources. In addition, resource definition calls for evaluation of the stress regime and permeability with depth in HDR reservoir rocks. Several speakers noted that many "hot dry wells" found within the conductive haloes of hydrothermal systems might be used in both exploration and in artificial development of the HDR resource.

All geophysical and geological panels at the workshop agreed that a clearing-house for existing geological and geophysical data is needed for future comprehensive evaluations of the HDR resource.

I. INTRODUCTION

Hot dry rock (HDR) is defined as that part of a geothermal anomaly where the fluids needed for production of steam or hot water are lacking. Most of the world's geothermal resource is not present in the form of natural hydrothermal systems but as HDR. Development of this resource through the use of manmade geothermal systems is in progress in several countries. The largest of these experiments, the Fenton Hill HDR geothermal project, is funded by the U.S. Department of Energy and the governments of West Germany and Japan. This project is located a short distance west of the rim of the Valles Caldera in the Jemez Mountains of New Mexico. As the Fenton Hill experiments progressed it became evident that the location and extent of the HDR geothermal resource in other areas should be evaluated and that potential HDR drilling sites be located as part of a comprehensive program needed to encourage its development. Because the HDR resource lacks the sharp physical and chemical contrasts produced by natural fluids, it presents different exploration problems from those of conventional hydrothermal exploration. The purpose of this workshop, held in Los Alamos, New Mexico, 21-23 June, 1982, was to review geological, geochemical, and geophysical exploration methods currently used for HDR recognition and resource evaluation, and to evaluate new ideas for HDR exploration.

A list of workshop attendees, the agenda, and the papers presented at the workshop are in the Appendix.

II. HEAT FLOW CRITERIA FOR HDR EXPLORATION

Heat flow, because it involves direct temperature measurements, is usually the ultimate standard for evaluating geothermal potential. Its importance increases as the scale of resolution narrows to that of choosing drilling sites.

Crustal heat flux varies between regions of relative geological stability such as eastern or midwestern North America, and the more active regions like western North America where crustal temperatures are usually hotter.

For stable regions J. Costain (Virginia Polytechnic Institute and State University) cited several geological settings that seemed promising for HDR. These take advantage of the fact that heat flow is the product of thermal gradient and thermal conductivity; therefore, regions of low thermal conductivity can have rather high thermal gradients and hence high temperatures at moderate depths, even though heat flow is only average. Heat flow is further enhanced if local crustal heat generation is high. Hence, two interesting HDR possibilities would be regions of normal gradient but deep, relatively insulating sedimentary rock and regions of high heat generation, such as a granitic pluton overlain by "blanketing" sedimentary layers. W. Hinze (Purdue University) elaborated upon some variations where crustal heat is concentrated by a local good conductor such as a salt dome, by hydrothermal circulation, by residual magmatic heat, or by upper mantle sources whose thermal effects have not yet diffused to the upper crust. Hinze cited thermal anomalies within the Mississippi Embayment as a possible example of "channelling" by a good conductor. K. German (University of Nebraska at Lincoln) attributed high temperatures in western Nebraska to the hydrothermal circulation mechanism, as did D. Hodge (SUNY, Buffalo), to explain high bottom-hole temperatures in basement rock near Auburn, New York.

Hence, from the standpoint of heat flow methods HDR exploration in older "stable" continental crust involves three criteria: (a) locating regions of relatively high heat flow, (b) identifying regions of low thermal conductivity, and (c) determining radiogenic heat production in basement rock.

Because of a far greater density of thermal anomalies, tectonic zones such as the western U.S. have enjoyed a much higher level of geothermal exploration, and many geothermal areas have been identified. Thus, an obvious HDR exploration technique cited by D. Blackwell (Southern Methodist University) and M. Smith (Los Alamos National Laboratory) is to obtain heat flow data in the "conductive haloes" surrounding known hydrothermal sites. Indeed, these areas often have sufficient numbers of "dry holes" to make them more interesting as HDR sites than as conventional sites. Steep geothermal gradients are, of course, direct indicators of high temperatures at accessible depths, but Blackwell indicated the need for a more reliable and easily interpreted way of using heat flow to project thermal effects to great depth. Ground water and hydrothermal water circulation add further complications, including extremely high apparent surface heat flow, but there is a growing body of experience in modeling these situations.

Further Work in Heat Flow Methods

The outlines for adequate heat flow criteria in HDR exploration are given above. However, the panel noted that these criteria could be improved and systematized by some additional efforts.

(1) A higher density of heat flow determinations would be extremely useful; it is particularly important to extend measurements beyond the immediate area of a wet geothermal or HDR site in order to reduce ambiguity in interpretation of heat flow data and to better model convective heat transfer.

(2) Better communication between the academic community and the geothermal industry would be beneficial in obtaining basement temperatures and cores for measurement of basement temperature, thermal conductivity, and heat generation.

(3) The Decade of North American Geology (DNAG) series of maps could serve as the outlet for four additional maps:
   (a) temperature at top of basement,
   (b) basement heat production,
   (c) heat flow at basement surface, and
   (d) surface heat flow.

III. SEISMIC CRITERIA FOR HDR EXPLORATION

If one were to look only at the relatively small effects, due purely to temperature, on seismic velocities, then only subtle variations in seismological observations would be observed. The utility of seismic methods is in determining crustal structure and thermally associated but often indirect phenomena such as the presence of fluids.

Many of the seismic methods are so well established that they are almost taken for granted. W. Laughlin (Los Alamos National Laboratory) described reflection surveys that were used to characterize depth to basement at the first HDR site at Fenton Hill, New Mexico. Magma bodies are potential HDR thermal sources and S. Kaufman (Cornell University) showed how reflection profiles helped define a magma layer intruded beneath the vicinity of Socorro, New Mexico. L. Braile (Purdue University) mentioned the strong structural controls provided by seismic refraction in the Yellowstone-Snake River Plain region; these included substantial velocity decreases, as much as 30%, attributed to fluids. Although the fluids would not themselves be the object of HDR exploration, they could contribute to heating nearby rock in the "conductive halo."

Seismic methods are particularly well suited to locating disturbed zones that have been heated hydrothermally or by magma. K. Aki (Massachusetts

Institute of Technology) noted that almost all the hot zones currently established as geothermal sites are characterized by deep crustal low-velocity cores. These comprise not only giant systems such as Yellowstone, but also the Jemez Caldera (although velocity surveys inside and outside the caldera did not play a role in originally choosing this HDR geothermal site). Three-dimensional teleseismic P-wave delay studies have strikingly outlined several low-velocity cores that represent hot rock that provides heat both to the local hydrothermal systems and to the halo of hot but dry rock. Seismicity serves to delineate possible HDR reservoirs in a number of ways: it can locate possible intrusions such as the Socorro magma layer; on the local scale it can provide information on stress directions as a guide to drilling. Contrary to the case for conventional reservoirs, seismicity is a negative indicator for manmade systems because of the danger of induced earthquakes and of water loss through active faults.

Some of the applications and information supplied by seismic methods are summarized in Table I.

Further Work in Seismic Methods

Future work in seismic HDR exploration should take advantage of those properties that are most sensitive to crack structure and pore fluids as ways to define the general form of geothermal structures:

(1) Teleseismic S-wave structure to define 3-D structure as done for P-waves.
(2) Determination of S-velocities, Poisson's ratios, and Q^{-1} in refraction surveys.
(3) Controlled surface wave studies to improve resolution of V_s and Q_s^{-1}.
(4) Detailed studies of known conventional hydrothermal and HDR areas to gain experience in seismically defining these reservoirs.

IV. MAGNETOTELLURIC CRITERIA FOR HDR EXPLORATION

Electromagnetic methods, magnetotellurics (MT) in particular, are extremely useful in geothermal exploration because of the sensitivity of rock conductivity to water content and to elevated temperatures. MT can target HDR resources in two important ways. As a regional exploration method, MT can be used to map the crustal deep electrical conductor. M. Ander (Los Alamos National Laboratory) showed five long two-dimensional models developed from approximately 200 MT soundings in Arizona and New Mexico. These models

TABLE I
CHARACTERISTICS OF SEISMIC PARAMETERS RELATED TO HDR EXPLORATION

	Teleseismic Residuals	Reflection Profiling	Refraction Profiling	Seismicity	Surface Wave Studies
Parameters	3-D distribution of Vp	Vp, Vs sometimes measured, f generally 8-50 hz, reflection coefficients, Q^{-1}, Poisson's ratio.	Compressional velocity, sometimes amplitude variations and Q^{-1} structure; f generally 1-20 hz. Parameters may show dependence on temperature although expected to be near limit of resolution. Useful for structural mapping which may relate to HDR potential.	P and S velocities must generally be assumed although P/S velocity ratio can be determined for an area. Earthquake locations and focal mechanisms are determined. Stress directions from focal mechanisms are useful for HDR exploitation. Presence of earthquake activity correlates with major geothermal anomalies associated with tectonically active areas. Not known to be associated with thermal anomalies in cratonic regions. Seismicity may indicate fracture porosity.	Surface wave dispersion is most sensitive to variations in shear wave velocity but can also be used to study Vp and density in ideal circumstances. Two-station techniques can be used to determine Q^{-1}. Relatvely low frequencies are normally used but studies of quarry blasts have successfully determined dispersion curves to periods of approximately 1 sec.
Resolution	Limited mainly by the station spacing, usually poorer than 10 km. The finest resolution so far achieved is 5 km for Coso, which is probably optimal considering the wavelength of typical teleseismic P waves.	Vertical resolution $\sim$100 m ($\lambda/4$) horizontal resolution $\sim$300-500 m.	Bodies on the order of several km or larger may be adequately mapped.	Dependent on seismograph array parameters. If sufficiently dense array available, seismicity associated with thermal anomalies of dimensions on the order of kilometers can be indicated.	Normally surface wave studies are considered to be of low resolution. However, controlled experiments could produce relatively high resolution results in areas where the near surface geology is simple (i.e. flat lying layers). A major limit to resolution is the difficulty of dealing with two-dimensional earth models.
Depths	Depth of probing comparable to the size of aperture.	Entire crust, if sufficient energy penetration.	May be applied to bodies at virtually any depth, certainly within the crust, but resolution generally degrades with depth.	Applicable to any depth.	Surface wave studies can be "tuned" to the depth of interest because the depth of penetration is dependent on frequency. Long period waves (50-150 sec) are routinely used to study the upper mantle. The "ground roll" of reflection surveys can be used to study near-surface layers.

TABLE I (cont)

	Teleseismic Residuals	Reflection Profiling	Refraction Profiling	Seismicity	Surface Wave Studies
Magmatic Target Characteristics	Molten body or partially molten body of size greater than about 10 x 10 x 10 km^3 having a velocity contrast of a few % from the surrounding rock.	Molten body: seen as large reflection coefficient. Partial melt: possible reflection and velocity anomaly.	Molten body: anomalous P/S velocity ratio, amplitude (wide angle reflection coefficient) and attenuation expected. Low P velocity expected but may not be large enough effect to be measurable. Partially molten body: Same as for molten body but anomalies will be smaller.	Seismic noise studies have also been used to locate both hydrothermal anomalies and magmatic intrusions.	Many anomalous conditions associated with targets are most pronounced in terms of S-wave velocity. Surface waves can be particularly useful for targets that can be expected to substantially affect Vs.
Solid HDR Target		Probably not	If temperature contrast is large enough (on the order of 100°C) as compared with adjacent rocks, similar anomalous seismic wave parameters as those described for molten rock may be observed.	Absence of seismicity.	Probably not
Remarks	The method has so far detected low-velocity-bodies (most likely partially molten) in the crust and upper mantle beneath all the studied geothermal areas in the western U.S. except under volcanoes in Cascades. Method could conceivably be applied to attenuation and S-wave velocities.	Satisfactory statistics, suitable energy source, and adequate velocity information required.			

indicate strong evidence for a correlation between the depth to deep electrical conductor and surface heat flow as well as with regional tectonics. One of these models, from Seligman to Yuma, Arizona, was used in a presentation by C. Aiken (University of Texas) and M. R. Hong (University of Texas) to indicate a correlation between the depth to the deep crustal conductor and the depth-to-Curie point. M. Ander and T. Shankland (Los Alamos National Laboratory) showed results of a correlation study of worldwide MT field data and crustal temperature obtained from surface heat flow. A pronounced result of their study was that even the most resistive crustal regions have conductivities several orders of magnitude better than laboratory samples and that this is easily explained by the presence of volatiles, water in particular. Most importantly, the data could be well represented by a straight line fit on a log vs 1/T plot indicating an excellent correlation between crustal electrical conductivity and crustal temperature. G. R. Jiracek (San Diego State University) suggested that the deep crustal electrical conductive horizon may occur where an impermeable, ductile cap traps pore fluids beneath. Ductile flow mechanisms are thermally activated processes that involve charge defects, lattice dislocations, or atomic diffusion, all of which enhance solid state electrical conduction. If active magma injection destroyed the integrity of the ductile cap, trapped fluids would escape, resulting in an overall decrease in conductivity. The final electrical signature would depend on thermal gradient, relative impermeability of the cap, extent of the pore fluids beneath, and amount of magma intrusion. Because temperature would likely be the major variable in a given geologic province, Jiracek also felt that the depth of a conductive layer, even if caused by a ductile layer, would provide a measure of the thermal gradient. Therefore it is likely that estimates of crustal temperature and regional heat flow can be obtained from estimates of the depth to crustal electrical conductor.

As a local exploration method MT can be used to map the structure of resistivity changes at a potential HDR site. This requires high-quality MT data and a tight MT station spacing. For both the regional and site specific exploration, problems exist in modeling and in interpreting the field results. A. Orange (Emerald Exploration, Inc.), S. Park (Massachusetts Institute of Technology), and D. Chambers (Woodward-Clyde Consultants, Inc.) discussed the nature of some of the pitfalls of MT interpretation in both two- and three-dimensions. MT interpretation is a complex art, even in many cases where the data appear straightforward; recognition of this complexity is a major step towards the realization of the method's full capabilities. Intense study of a wide variety of two- and three-dimensional models will provide the interpreter with valuable, critical insight. Most importantly MT surveys should be planned using this insight.

Further Work in Electromagnetic Surveys

The electromagnetics working group had several specific recommendations for further work.

(1) In the past decade well over 5000 MT soundings have been completed in the United States. These represent an extraordinarily valuable data base for determining the depth to the deep electrical conductor. It was suggested that these data be compiled in a single data base and analyzed. An international project to do this has been endorsed already by the National Academy of Science. This would be of value in further confirming the correlations between electrical conductivity, heat flow, depth-to-Curie point, and regional tectonics.

(2) A continuous exploration program using electrical methods should be directed toward locating conductivity anomalies in the United States. These could be either hydrothermal or HDR systems. The distribution of heat flow and electrical properties may well be useful in differentiating the two types of systems.

(3) A major uncertainty exists in knowing how to interpret enhanced electrical conductivities in the crust. Possible mechanisms are numerous. Although we have some measure of understanding of these effects, there is insufficient information to judge how these effects persist over time. For instance, can pore fluids persist in enhancing conductivity over geologic time at temperatures of several hundred degrees or do they form hydrated minerals and hence change rock conductivity? In addition, long-term measurements of electrical conductivities in rocks need to be undertaken at geologic temperatures and pressures to understand changes with time.

V. GRAVITY AND MAGNETIC CRITERIA FOR HDR EXPLORATION

There are many ways in which gravity and magnetic methods can be applied to exploration for HDR resources. Gravity analysis is well suited for mapping depth to rocks with low permeability. Magnetic methods are not usually as well suited for this because magnetic "basement" seldom coincides with geologic "basement." Gravity can be used to some minor extent in studying the nature of the sedimentary blanket. Both gravity and magnetic surveys are important methods for delineating both regional and local structure in the Phanerozoic and the basement. They are particularly good for locating faults, suture zones, and old rift structures. Magnetic surveys may be used to determine depths to the Curie isotherm. A shallowing in the depth to the Curie isotherm may suggest a thermal upwelling and therefore a possible HDR target area.

J. Costain, L. Glover (Virginia Tech), D. Hodge, and K. Fromm (SUNY, Buffalo) described the use of gravity data in targeting HDR sites in the eastern U.S. while W. Hinze, L. Braile, R. von Frese (Purdue University), G. R. Keller, R. Roy (University of Texas at El Paso), and P. Morgan (Lunar and Planetary Institute) described gravity applications in the midcontinent U.S. In these studies, gravity and magnetic data covering broad regions have been observed, compiled, and in some cases filtered to enhance particular attributes of the anomaly field. These maps are proving useful reconnaissance tools in mapping tectonic/lithologic regimes that serve as guides to localize more detailed geophysical and geologic studies. In particular, gravity and magnetic surveys have helped in investigations of silicic and alkalic intrusive bodies, which are potential radiogenic heat sources. Silicic intrusives are commonly characterized by gravity minima of the order of a few tens of milligals and negative magnetic anomalies. However, some plutons studied in the midcontinent are associated with relatively high magnetite contents resulting in strong localized magnetic anomalies. The gravity signature of these high-magnetite plutons is absent or slightly positive. By contrast, alkalic intrusives are generally marked by both intense positive gravity and magnetic anomalies.

In two separate papers, I. Won (North Carolina State University), C. Aiken and R. Hong discussed the inversion of magnetic data to determine the depth-to-Curie point isotherm. Aiken and Hong described how depth-to-Curie point estimates they made along a profile from Yuma to Seligman, Arizona, correlated with estimates of depth to deep crustal electrical conductor made along the same profile by M. Ander using MT data.

Further work on gravity and magnetic methods

The gravity and magnetic working group identified several areas for further work in applying gravity and magnetic methods to HDR exploration.

(1) More case studies are needed.

(2) Petrophysical studies are needed to obtain precise measurements of density and magnetization of rocks of interest. Studies addressing the magnetization of rocks as a function of temperature for extended times are considered especially important.

(3) Gridded filtered data sets must be generally available.

(4) Although magnetic maps are widely available, digital magnetic data are not. It would be useful to make such data available.

(5) It would be profitable to further study the correlation between the depth-to-Curie isotherm estimates and surface heat flow and the depth to the deep crustal electrical conductor.

VI. GEOLOGIC METHODS FOR HDR EXPLORATION

Geologists attending the workshop all emphasized a multidisciplinary approach to HDR exploration. Their role is to provide the geological framework for geophysical data in regional HDR surveys and to characterize the genesis and thermal history of heat sources within geothermal areas associated with recent volcanism or older silicic plutons. The geologist's role has changed little since the Hot Dry Rock Resource Evaluation Panel (HDRAP) of the Energy Research and Development Administration defined the variety of geological surveys needed for HDR exploration and development.

Within igneous systems, which make up most of the known geothermal resource areas (KGRA's) of the United States, the geologist's role in defining the HDR resource is substantial. To understand the extent and magnitude of hydrothermal and HDR components of an igneous system requires detailed information on the structural setting, ages, distribution, volume, and composition of volcanic units, and the hydrologic setting and chemistry of rock-water interactions within the system. The rate of fracture formation and fracture healing within these systems must be determined. All of this resource definition requires drilling and careful analysis of cores, cuttings, and geophysical well logs.

One of the most useful data sets for the geologist is from the many wells drilled for hydrothermal development that have high temperatures but no production of fluids. By keeping records of "hot but dry" wells within KGRA's, the high-grade HDR resource may be best evaluated.

Examination of regional thermal anomalies is mostly in the realm of geophysical surveys. However, the characterization of HDR reservoir rocks depends upon good physical and petrologic studies.

E. Padovani (National Science Foundation) discussed the utility of petrology of xenoliths from young volcanic rocks as a tool for geothermal evaluation. It is possible to use mineralogic geobarometers and geothermometers to calculate thermal gradients; these serve well as supplements to measured heat flow.

A major problem in HDR resource evaluation is determination of changes in the stress regime and permeability with depth in a variety of geologic settings. These data are needed for identification of rock units to serve as HDR reservoir rocks.

Compilation and evaluation of existing geological and geophysical data would be easier if there were a clearinghouse for published and proprietary information. Also needed are better curatorial facilities for the preservation of drill cores and cuttings; perhaps such facilities could be established through a continental scientific drilling program.

VII. CASE STUDIES

W. Laughlin and M. Smith described the process of selecting the first hot dry rock geothermal site in the Jemez Mountains, New Mexico. Of primary importance to site selection was the published data available on the extent, age, and nature of the Valles Caldera. Heat flow measurements along the western edge of the caldera, structural mapping and a slim exploratory drill hole to the Precambrian "basement" were key factors in site selection. Determination of the degree of faulting and jointing within the plutonic-metamorphic reservoir rocks was not possible and could be determined only by drilling. Drilling slim exploratory holes, with numerous cores, provides many of the answers and appears to be the best local site evaluation technique; it certainly was at the New Mexico site.

Hodge and Fromm used heat flow, temperature gradients, and gravity surveys to search for hidden thermal anomalies in the northern Appalachian basin. Initial results indicate that variations in temperature gradients are due to heat generation in granitic plutons in the basement (similar to the anomalies described by J. Costain in the Atlantic coastal plain). Recent drilling in western New York state has indicated that not all thermal anomalies are related to buried granitic plutons; some appear to be the result of hydrothermal circulation along faults and fractures within the basin.

Heat flow measurements, bottom-hole temperatures in oil and gas wells, and residual Bouguer gravity maps were the basis of a geothermal resource assessment of Nebraska by Gosnold and German (University of Nebraska). Two areas within the state have high heat flow. Within the panhandle of Nebraska the anomalies appear to be due to updip flow of deep aquifers from the Denver-Julesberg basin. High heat flow within north-central Nebraska is more difficult to explain; it may be related to water flow along fractures into the Dakota group or to buried granitic plutons. More drilling into Precambrian basement rocks is needed to evaluate the HDR geothermal resource of Nebraska, but its potential seems high.

Geothermal exploration strategies used in the Rhine graben by the European Communities were presented by B. Hoffers (Los Alamos National Laboratory and Gerwerkschaft Walter). These include: (1) work on the gneisses and schists of Hercynian age, granites of Carboniferous age, and Paleozoic sedimentary rocks, (2) bottom-hole temperatures and heat flow measurements, (3) Bouguer gravity anomalies, and (4) tectonic analysis. Diapiric rise of mantle under the Rhine graben and higher temperature gradients were identified through the use of, in addition to those surveys described above, refraction and reflection seismic profiles, MT surveys, aeromagnetic surveys, and electrical surveys.

APPENDIX

ATTENDEES, AGENDA, AND PAPERS PRESENTED AT WORKSHOP ON EXPLORATION OF HOT DRY ROCK GEOTHERMAL SYSTEMS

ATTENDEES

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Al Weibel
Portland, Oregon

Francis West
New Mexico State Engineer's Office

John T. Whetten
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Ihn J. Won
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AGENDA

HOT DRY ROCK EXPLORATION WORKSHOP

National Security and Resources Study Center
Los Alamos National Laboratory

Monday, June 21, 1982

Opening Remarks

Session I: P. Morgan, Chairman

M. Smith, Hot Dry Rock is Where you Find It
D. Blackwell, Heat Flow - The Technique for Hot Dry Rock Exploration and Evaluation
J. Costain, Geothermal Energy in the Eastern United States: The Radiogenic Model

M. Ander, Magnetotellurics Applied to Hot Dry Rock Geothermal Exploration in Arizona and New Mexico
G. Jiracek, Interpretation of Magnetotelluric Soundings for Hot Dry Rock Prospecting

Session II: F. Goff, Chairman

A. Orange, Some Effects of Two and Three-Dimensional Structure on Magnetotelluric Data
I. Won, Determination of Depth to the Curie Isotherm from Aeromagnetic Data
K. Aki, 3-D Seismic Velocity Anomalies in the Crust and Upper Mantle Associated with Geothermal Areas in the Western United States

S. Kaufman, Continental Structure
G. Heiken, Hot Dry Rock Geothermal Site Selection
A. W. Laughlin, Fenton Hill Site Selection and Evaluation: A Case History.

Tuesday, June 22, 1982

Session III: C. Aiken, Chairman

W. Hinze, Geophysical Exploration for Hot Dry Rock in the Midcontinent
L. Braile, Seismic Methods of Hot Dry Rock Exploration
D. Hodge, Geothermal Anomalies in the Northern Appalachian Basin; Western and Central New York

K. German, Geothermal Investigations in Nebraska
B. Hoffers, Geothermal Exploration in the Rhine Graben (West Germany and France)
T. Meidav, Parametric Exploration for Hot Dry Rock

Meetings of Working Groups
- J. Costain, Chairman, Heat Flow - University House
- W. Hinze, Chairman, Gravity and Aeromagnetism - Study Center
- G. Keller, Chairman, Electromagnetic Methods - University House
- L. Braile, Chairman, Seismology - Study Center
- E. Padovani, Chairman, Geology and Geochemistry - University House

Reports of Working Groups

Wednesday, June 23, 1982

Field Trip to Fenton Hill Hot Dry Rock Geothermal Site

HOT DRY ROCK IS WHERE YOU FIND IT

Morton C. Smith
Earth and Space Sciences Division
Los Alamos National Laboratory
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Because the earth's interior is very hot and the upper crust is a poor thermal conductor, the heat stored in crustal rock at practical drilling depths represents by far the largest supply of usable energy that is accessible to man. At least to me, it seems inevitable that -- as our limited supplies of fossil and nuclear fuels dwindle and become more expensive -- this vast reservoir of thermal energy will eventually be exploited to mankind's benefit all over the world. Much of its use will be direct -- for space heating, processing foods and chemicals, and a wide variety of other low-temperature applications. However, where relatively high temperatures are encountered at reasonable depths, it will of course also be used to generate electricity.

Some small fraction of this geothermal energy -- probably much less than 1% -- is stored in hydrothermal reservoirs, representing a useful and economical, but limited, energy resource. The rest is in the rock itself, and it is with this "essentially inexhaustible" energy supply that the Hot Dry Rock (HDR) Program is concerned.

In principle, naturally heated crustal rock can be of any type and in any physical condition -- and a means can be proposed for extracting heat from it in almost every conceivable geologic situation. For example, the Soviets propose to recover large quantities of low-grade heat by a water-flooding operation in a highly permeable sandstone. Gunnar Bodvarsson proposes forced circulation through natural fractures in fault systems, within or adjacent to dikes, or along the interfaces of successive basalt flows. The British and the French propose to circulate through reopened natural fractures in old, weakly sealed, crystalline rock. Some years ago, Robert M. Potter proposed forced horizontal circulation between vertical hydraulic fractures in formations with low but significant matrix permeability. These and a variety of other HDR concepts appear worthy of serious investigation.

At Los Alamos, however, we have so far concentrated on only one type of HDR environment and one method of heat extraction. We have assumed that, at depths and temperatures of geothermal interest in regions undisturbed by recent large-scale earth movements, the normal situation at depth is hot rock with very low initial permeability and free-water content. This is ideal for containing a pressurized-water heat-extraction loop, but construction of such a loop requires creation of flow passages in the rock with large surface areas for heat transfer. For loop construction, we have concentrated on the use of hydraulic fracturing to connect two vertically separated wellbores.

Conceivably, in a deep sedimentary basin, the low-permeability HDR thermal reservoir might be a massive body of shale or dolomite or limestone, or even an initially permeable formation tightly sealed by alteration products or mineral deposition. However, the better choice in general has seemed to us to be the crystalline basement. Once this has been penetrated to a sufficient depth to reach a usefully high temperature and desirably low permeability, one is reasonably assured that the thermal reservoir is large both horizontally and vertically -- with the advantage that if a higher temperature is required, one need only drill a little deeper.

For some reason that I do not understand, a mystique has developed that it is somehow more difficult to locate and characterize an HDR thermal reservoir than a hydrothermal reservoir. As a nonexpert in geothermal exploration, it seems to me that the opposite must be true. It appears that it should certainly be easier to demonstrate the absence of a hydrothermal reservoir than to demonstrate its presence. As I understand it, aside from obvious surface manifestation, the principal evidence for existence of hot water at depth is low electrical resistivity. Since this may result from other causes than the presence of hot water (e.g., permeation by a highly saline brine, mineral alteration to clays or zeolites, a layer of shale, or a mineral deposit) it is not definitive, and a shocking proportion of dry holes has resulted from drilling where the experts predicted the presence of hydrothermal reservoirs.

In exploring for hot dry rock, the obvious first approach is simply to locate those hot dry holes (which of course we have already done, so far as we could). In their absence, or if they are found only in areas already leased, one should probably resort to fairly conventional exploration techniques but avoid areas where there are high-conductivity anomalies at depth. Conceivably this could ultimately result in drilling into a steam field (which would be a scientific but not a financial disaster), and this constraint may be overly conservative since it would eliminate from consideration areas where the anomaly represented something other than hot water. However, there appear to be enough really good HDR areas so that we can afford to pass up the doubtful ones.

If the energy system is to be developed by hydraulic fracturing and operated as a recirculating pressurized-water loop, it is desirable that it be constructed in a large, shallow body of hot rock with very low matrix and fracture permeability. The lateral extent of the area should be not less than several square kilometers, to provide for construction of a group of parallel systems. (This can of course be put in terms of an investigation of the nature of the heat source.) To avoid extending the fracture system to the surface or to overlying permeable formations, it is important that the top of the fractures be not less than a few hundred meters below the top of the reservoir formation. Otherwise, the shallower the better, primarily to minimize drilling costs but also to reduce overburden stress and pumping pressures required to create and extend hydraulic fractures.

In our present state of knowledge, we believe that the most desirable type of reservoir formation is the crystalline basement, whether volcanic, plutonic, or metamorphic. Since we would like to reach a high temperature at shallow to moderate depth, a high conductive geothermal gradient, persistent with depth, is obviously desirable. Because crystalline rocks are relatively good thermal conductors, this is favored by the presence of a few hundred meters of poorly conductive sediments or volcanics above the basement -- so long as there is no significant cooling by active ground-water circulation. (If you prefer, this can be put in terms of conductive and convective heat transport, and internal heat generation may also be important.) For predictability of fracturing behavior, it would be useful if the reservoir formation were reasonably uniform and isotropic, and very helpful if the stress condition at depth were known. Natural fracture systems are to be avoided, because of the dangers of excessive leakage from the pressurized-water loop and of triggering earthquakes by injecting a pressurized fluid. All of this requires (1) a careful temperature-gradient (or heat flow) study; (2) detailed geological, hydrological, and geophysical investigation of the area; (3) identification of any currently or recently active faults; and (4) review of the seismic history of the area.

In the absence of an existing deep hole, information at this point will necessarily be limited to that collected at the surface and from shallow holes, and little will be known about hydrology at depth and basement rock structure. The next step, therefore, should be to drill a slim hole that penetrates the basement rock by at least a hundred meters and preferably more than that, and is left uncased in the basement section. That section should if possible be cored continuously and the cores examined for chemical, mineralogical, physical, and mechanical properties, altered zones, and sealed and unsealed fractures. The entire hole should be logged for temperature, and geophysical logs run in the uncased basement section to learn as much as possible about the rock around the hole and in any uncored intervals. The borehole wall should be examined with a televiewer for initial structure and reexamined after a series of hydraulic-fracturing and pressure-flow tests. By drill-stem or other tests, permeability should be determined locally wherever there are indications of fluid loss, unusually high drilling rates, or altered or fractured zones.

All of this is expensive and time consuming, but much less so than drilling a deep, full-size hole in the wrong place.

HEAT FLOW - THE TECHNIQUE FOR HOT DRY ROCK EXPLORATION AND EVALUATION

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Heat Flow Techniques for Hot Dry Rock Evaluation

In its idealization, the hot dry rock (HDR) concept involves location and exploitation of an area where the rocks are at a high enough temperature and are impermeable enough to allow artificial fracturing and exploitation of water circulated through the produced fractures. This low-permeability setting is also ideal for heat flow measurements. Heat flow is determined as a product of the geothermal gradient times the thermal conductivity. Geothermal gradients are obtained from measurements of temperature versus depth in a drill hole and the thermal conductivity is measured on cuttings or core samples from the hole. If thermal conductivity is uniform, then the geothermal gradient and heat flow vary together. In most areas, however, there are significant lateral and vertical variations in thermal conductivity and thus gradient measurements over a limited depth range will have little direct usefulness for HDR exploration as the gradients will vary within the borehole and laterally due to changes in lithology.

Recent attempts to compile regional gradient maps have had the objective of geothermal evaluation both for hydrothermal resources (Gaffanti and Nathanson, 1980) and HDR resources (Kron and Heiken, 1980). The maps prepared by these two groups bear little resemblance to one another, however (see Blackwell, 1981). The futility of evaluation using this technique is clearly demonstrated by a hole in Kansas (Fig. A-1, from Blackwell and Steele, 1981). The heat flow is constant in this hole at 1.4 cal/cm^2 sec, yet the geothermal gradient varies by a factor of 4 (from approximately 15°C/km in the bottom of the hole, to approximately 50°C/km in the upper part of the hole). The variation is solely related to changes in thermal conductivity so mere determination of a geothermal gradient over "some interval" for this locality contains little useful information, either for extrapolation to depth or evaluation of the temperature at a specific horizon. Another example is shown from Fig. A-2, also from Kansas. The intricate correlation of gradient with lithology is shown by a comparison of the gradient logs with the gamma and sonic velocity logs. If information is available on the thermal conductivity

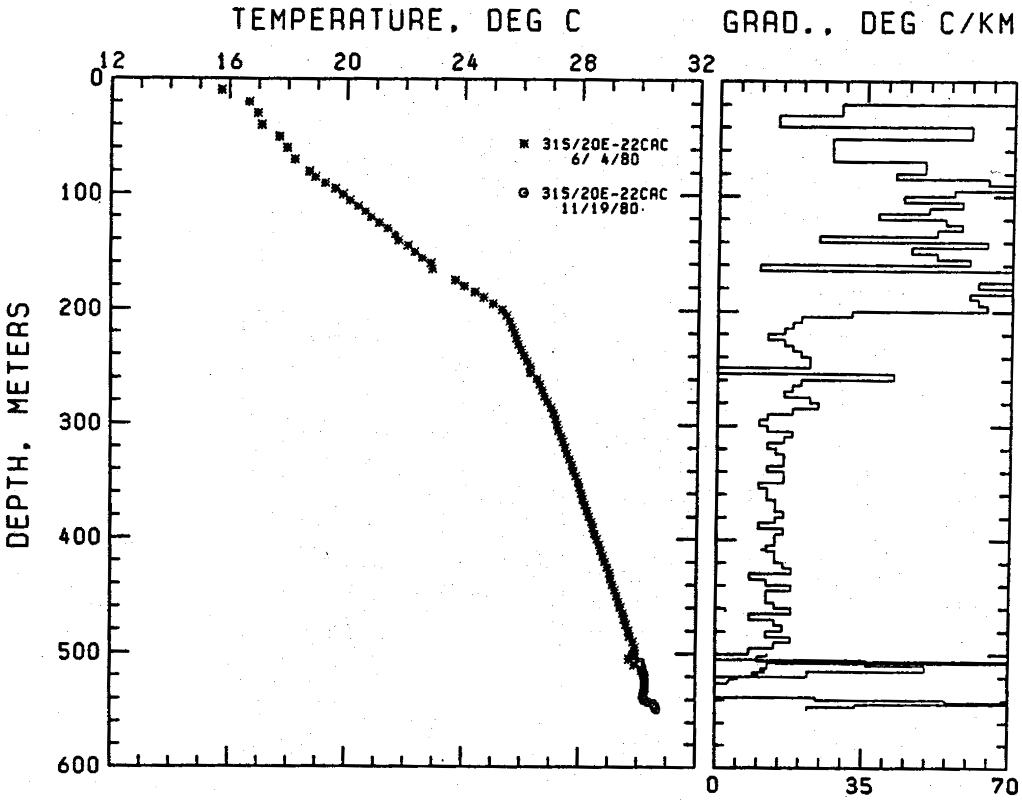

Fig. A-1.
Temperature-depth and gradient data for Kansas hole 31S/20E-22 cac (Blackwell and Steele, 1981).

of the geologic section involved, then a single gradient and thermal conductivity measurement and subsequent heat flow determination in a single interval is sufficient for calculation of the geothermal gradient in the remainder of the section (assuming that the heat flow is constant). Without such heat flow information however, a single measurement of temperature gradient is of little use. Therefore heat flow studies rather than gradient studies must be used in the HDR exploration.

Other geophysical techniques are used for geothermal exploration and evaluation. For HDR, however, it is questionable if such techniques have general applicability. As is the case with most exploration, the object in the HDR exploration program would be to locate the highest temperature at the shallowest depth in a given region. Temperature variations at depths of 2-5 km in regions of low permeability are likely to be virtually indetectable by gravity, seismic, electrical resistivity or magnetic studies unless there is an indirect relationship between temperature and some other property such as,

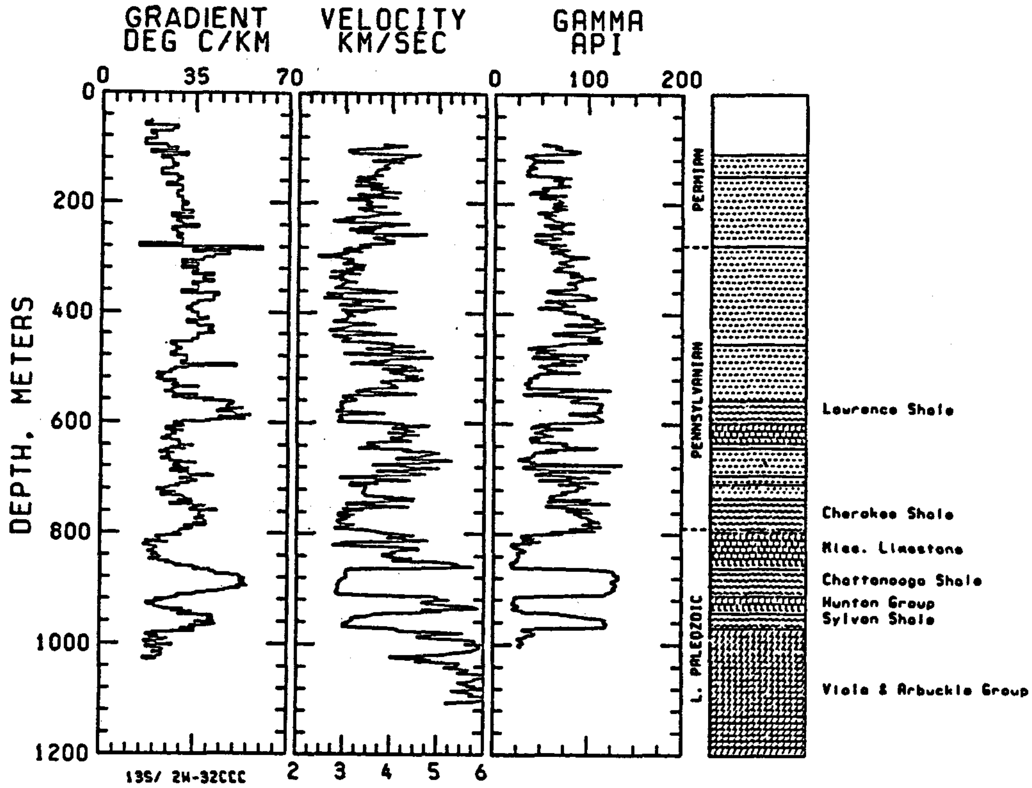

Fig. A-2.
Bar graphs of gradient, P-wave velocity, and natural gamma-ray activity and a generalized geologic section for Kansas hole 13S/2W-32 ccc.

for example, the correspondence of high radioactive areas (with consequent high heat flow) and low gravity anomalies as had been proposed for the eastern United States (Costain et al., 1980). Furthermore, most other geophysical techniques lose their resolution in the depth range 0.5-3 km and thus may not be useful in determining the deep thermal conditions (see Jiracek, 1981 for example). So the HDR exploration and evaluation program must emphasize heat flow techniques.

The main difficulty with the application of the heat flow technique is that in areas of complicated hydrology, it may not be easy to determine what the true heat flow is at depth. An example of this situation occurs at the site of the current HDR exploitation project. Apparently hot water flow laterally along the base of the Paleozoic section has progressed outward from the Valles Caldera. This causes the heat flow to be higher from the Paleozoic rocks, then from the basement. However, as discussed below, we have become much more proficient in recognizing locations for water disturbances on heat flow and have enough information for various areas in the U.S. to clearly recognize when problems exist and even to use the information from problem areas to determine certain quantities of geologic interest. For example, analysis of temperature-depth curves from the EE holes suggests that water flow outward from the Valles Caldera has been in existence for a period of about 10,000 years. The water flow is responsible for the upper curvature observed in the gradients.

Recent Advances in Heat Flow Studies in the United States

Investigations supported by the Department of Energy (DOE)/state-coupled geothermal-direct-heat program have resulted in collection of extensive new heat flow data in the past three years. A small part of this data base is discussed by Sass et al., (1981) and many hundreds more data points will be published in the next year or two as these projects are completed. As a result we have made major advances in our understanding of the regional variations of heat flow and controls on subsurface temperatures, all of which are significant to HDR evaluation and exploration. At this point, regionalization of heat flow and temperature is fairly well understood at a scale of 10-100 km. Also, in most areas there are now deep enough holes for evaluation of the heat flow, and subsequent gradient, variations with depth. In general, most of the interpretations of the shallow heat flow data are borne out but the deeper holes allow a more complete analysis of the impact of such variables as regional water flow on the deeper thermal conditions.

Important changes in our regional understanding with specific reference to HDR have been the discovery of a very large area of high temperature and low permeability in the Oregon Cascade range. In this area, a region at least 150 km long and 30 km wide has a mean temperature gradient of 60°C/km, which is as high as gradients typically associated with igneous systems. The impermeability of much of this province suggests that it may be a prime target for HDR exploitation. Furthermore, it also appears that large areas of the Mid-continent have much higher temperatures at depth than anticipated, even though heat flow values are quite modest. Particularly, studies have shown temperatures at the basement surface of 80°C and possible temperatures of 150°C at depths as shallow as 4 or 5 km over large areas of Nebraska and possibly Colorado, North and South Dakota (Gosnold and Eversoll, 1981). Also, we now understand that there are large conductive haloes surrounding all the high-temperature hydrothermal systems, whether igneous related or not. This halo occurs because the circulation in the geothermal system can be very effective at heating up the rocks surrounding the system. These areas are prime targets for the development of HDR geothermal energy because high temperatures occur at quite shallow depths. As more and more geothermal systems are discovered and evaluated, additional HDR regions will be discovered as well.

Summary

Heat flow rather than geothermal gradient must be used in HDR evaluation. Heat flow techniques are the most cost effective technique for exploring for HDR because of the specific nature of the technique, because of the extensive data base available, and because of the understanding of the controls on heat flow variations. Much new data has been developed through the DOE hydrothermal exploration programs and most of this data is directly applicable to the HDR program. Several large new areas of potential importance for HDR exploitation have been located. Many new local geothermal systems have been drilled that may be suitable for HDR exploitation as the technique is developed.

References

Blackwell, D.D., 1981, Aspects of low temperature geothermal assessment with examples from Kansas and Oregon, Glenwood Spgs. Tech. Conf. Mtg., V.1, DOE/ID/12079-39, ESL-59, pp. 1-22.

Blackwell, D.D., and J.L. Steele, 1981, Heat flow and geothermal potential of Kansas, Final Rept. to Kansas Geological Survey Contract No. 949, 69 pp.

Costain, J.K., L. Glover, and A.K. Singh, 1980, Low temperature geothermal resources in the Eastern United States, EOS, 61, pp. 1-3.

Gaffanti, M., and M. Nathanson, 1980, Preliminary map of temperature gradients in the conterminous United States, Geoth. Resources Council Trans. 4, pp. 53-56.

Gosnold, W.D., and D.A. Eversoll, 1981, Usefulness of heat flow data in regional asssessment of low temperature geothermal resources with special reference to Nebraska, Geoth. Resources Council Trans. 5, pp. 79-82.

Jiracek, G.R., 1981, Resistivity methods in exploration for hydrothermal resources, Glenwood Spgs. Tech. Conf. Mtg., V.1. DOE/ID/12079-39, ESL-59, pp. 23-40.

Kron, A.,and G. Heiken, 1980, Geothermal gradient map of the United States, Geoth. Resources Council Trans. 4, pp. 69-71.

Sass, J.H., D.D. Blackwell, D.S. Chapman, J.K. Costain, E.R. Decker, L.A. Lawver, and D.A. Swanberg, 1981, Heat flow from the crust of the United States, in Physical Properties of Rocks and Minerals, ed. K.S. Touloukian, W.R. Judd, and R.F. Roy, McGraw-Hill Book Co., New York, 503-548.

GEOTHERMAL ENERGY IN THE EASTERN UNITED STATES: THE RADIOGENIC MODEL

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The geothermal energy resource in the eastern United States is primarily a liquid-dominated, low-temperature system. Systematic efforts to estimate the geothermal resources of the entire United States have been made by the U.S. Geological Survey (White and Williams, 1975; Muffler, 1979; Sammel, 1979; Muffler and Cataldi, 1979).

The major factors that result in geothermal anomalies in the eastern United States are different than those in the West. For example, heat from radioactive decay is more important in the East. In the eastern United States, known geothermal gradients are in the range of 10° to 50°C/km. Gradients higher than 30°C/km are considered to be anomalously high. The geothermal gradient, $\Delta T/\Delta z$, is a function of <u>both</u> conductive heat flow, q, and thermal conductivity, K, because:

$$\Delta T/\Delta z = q/K.$$

High gradients will therefore be found where the local heat flow has a high value, and where the local thermal conductivity of rocks is low. As discussed below, high heat flow is characteristic of unmetamorphosed granites; low thermal conductivity is characteristic of sediments that blanket these granites. The efficient transfer and use of geothermal energy always requires convective transport of thermal energy by fluids. In all geothermal systems, the most desirable locations are those where the warmest fluids can be extracted from the shallowest depths. These locations are usually, but not always, coincident with regions where the conductive heat flow is highest.

Birch et al. (1968), Lachenbruch (1968), and Roy et al. (1968) showed that the local heat flow in the eastern United States is related to the concentration of uranium and thorium in surface rocks (mostly granite). Costain and Glover (1980) found a similar relationship in the southeastern United States. Isotopes of uranium (U), thorium (Th), and potassium occur in sufficient abundance and have half-lives sufficiently long to be important for heat generation from radioactive decay (Birch, 1954). Decay of a uranium atom produces about four times as much heat as the decay of thorium atom; however, Th/U ratios in many granite rocks are about equal to four so that thorium is usually as important as uranium. The heat generated from uranium and thorium in typical granites is about 85-90% of the total; heat from potassium decay is considerably less important, about 10-15% The immediate implication of this is that the distribution of uranium and thorium in the upper 10 to 15 km of the earth's crust is primarily responsible for the observed lateral variations in surface heat flow in the eastern United States.

Unmetamorphosed granite plutons and batholiths relatively enriched in uranium and thorium are exposed in the Piedmont Province (Fig. A-3). These Piedmont rocks are concealed to the southeast by a seaward-thickening wedge of Atlantic Coastal Plain sediments. Similar granitoids occur in these concealed Piedmont rocks, which are the basement beneath the Atlantic Coastal Plain.

Geothermal resources in the Appalachian Mountain System and the Atlantic Coastal Plain may be grouped into (I) water-saturated sediments of low thermal conductivity overlying radioactive heat-producing granites, (II) areas of normal geothermal gradient, (III) hot and warm springs emanating from fault-fracture zones as a result of leakage from greater depths, (IV) hot dry rock, especially radioactive granites beneath sediments of low thermal conductivity.

Resource I (Fig. A-4) is referred to as the "radiogenic model" (Costain et al., 1980) and has been the principal objective of the geothermal program at Virginia Polytechnic Institute and State University (VPI&SU). Temperature gradients are high in areas where the resource is found because heat-producing granite basement rocks are blanketed with a thick sequence of sediments of relatively low thermal conductivity (Fig. A-5). Large volumes of granite with low concentrations of uranium and thorium will increase the subsurface temperature substantially, and relatively higher temperatures will be found at shallow depths within sediments that overlie such bodies, as indicated in Fig. A-5. An understanding of the distribution of granites and of uranium and thorium in the basement rock is therefore important in order to define locations where the highest temperatures occur at the shallowest depths.

Optimum sites for the development of geothermal energy in the eastern United States probably will be associated with the flat-lying, relatively unconsolidated sediments that underlie the Atlantic Coastal Plain. These sediments have a relatively low thermal conductivity, and there are many

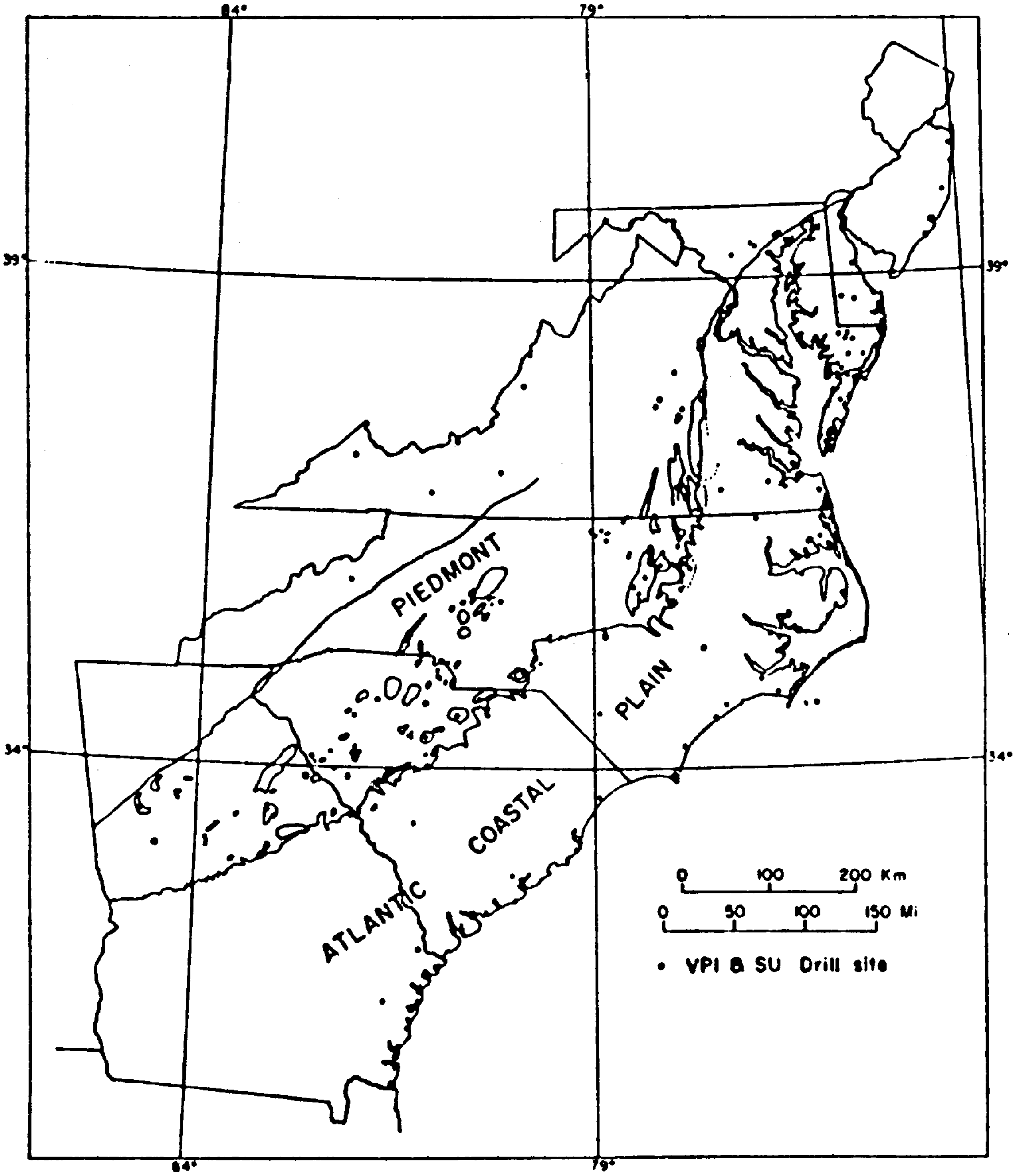

Fig. A-3.
Late Paleozoic syn- and post-Metamorphic granites in the southeastern United States.

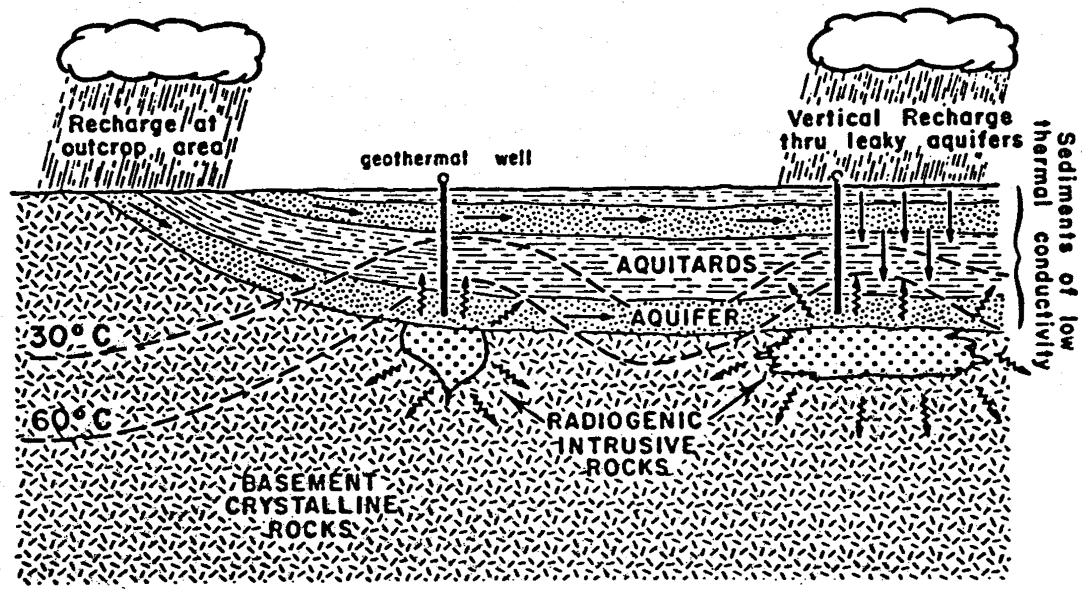

Fig. A-4.

Radiogenic model.

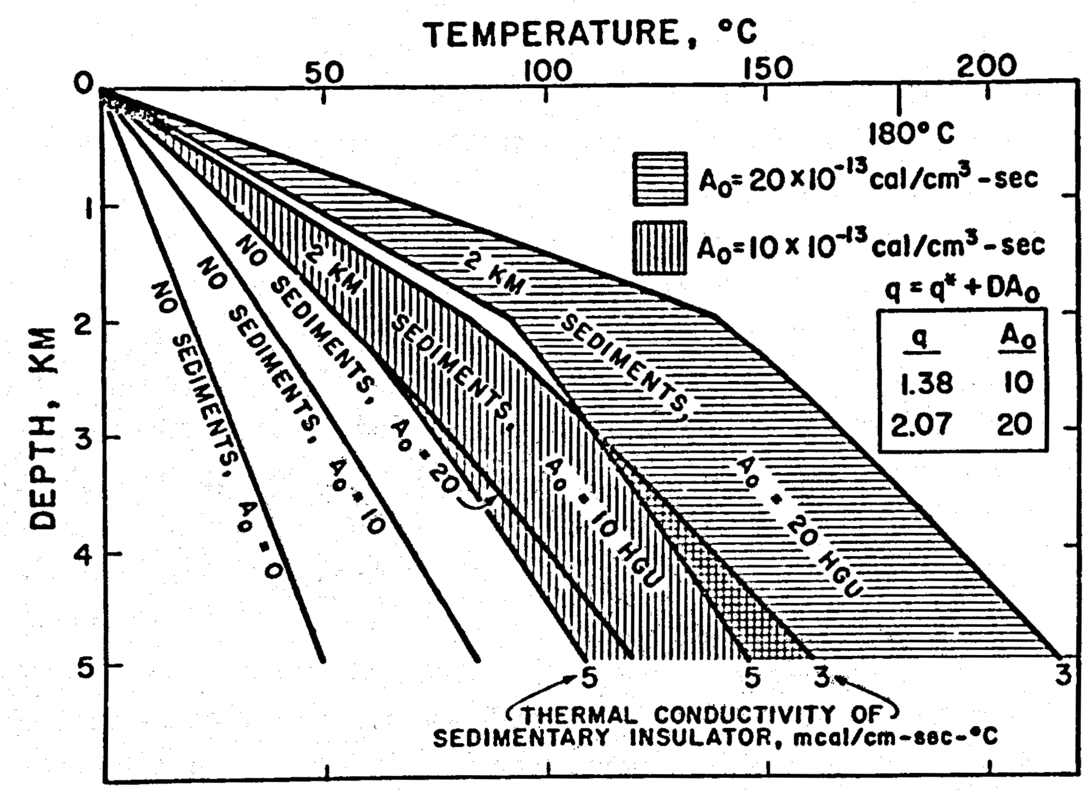

Fig. A-5.

Effect of sediment blanketing.

potential aquifers within the sandy, deeper parts of the sedimentary section that probably contain large quantities of hot water.

Resource II is widely available throughout much of the United States (Sammel, 1979). The entire Atlantic Coastal Plain would fall into this resource category. West of the Blue Ridge, thick sequences of Paleozoic sediments blanket crystalline basement rocks of unknown heat generation. In such areas, thick shales will result in higher geothermal gradients than carbonate rocks or sandstones, even where the heat flow is normal. As noted by Sammel (1979), the low-temperature geothermal waters of the central and eastern United States are known or inferred to be extensive. Their utilization is dependent upon identification of locations where conditions for recovery are economically favorable.

Resource III is found in the northwestern part of Virginia and adjacent parts of West Virginia, where approximately 100 springs have temperatures ranging from 9° to 41°C. The hottest springs are in the Warm Springs anticline in folded sedimentary rock of Paleozoic age in northwestern Virginia. All of the warm springs in the valley are grouped near topographic gaps apparently associated with vertical transverse fracture zones (linears) that cut across adjacent folds to the east and west (Geiser, 1976). Faults and/or joints play an important role in the location of the warm springs, because warm springs are always near gaps that probably have developed along zones of increased fracture or joint density.

There is no known association of warm springs with heat-producing granites. The origin of the warm springs in the Warm Springs Anticline in northwestern Virginia as proposed by Perry et al., (1979) is as follows. Meteoric water enters steeply dipping Silurian quartzites on the northwest limb and permeates to depths sufficient to heat the water in the presence of the normal geothermal gradient (about 10°C/km) near Hot Springs, Virginia. Ground-water flowlines near the surface and midway between the topographic gaps are approximately vertical (and parallel to bedding within the steeply dipping quartzites) because of the boundary condition imposed by the topographic relief between the gaps. At depth, the water moves horizontally and intersects east/west trending, vertical, transverse fracture zones. The temperature of the water issuing from springs located along the transverse fracture zones depends upon the depth reached by the water, and on the degree of its mixing with cooler, shallower water. Implicit in the model is the important requirement that the aquifer have an uninterrupted vertical relief large enough to allow the water to reach depths sufficient to heat it.

The water flow from Boiler Spring (40°C) at Hot Springs, Virginia, is 86,220 gallons/day (Hobba et al., 1979). The flow at Bolar Spring (22°C), about 20 km northeast of Hot Springs, is about 3,000,000 gallons/day. Because the total amount of heat released at the larger but cooler springs is much greater than that released at the smaller but warmer springs (Hobba and others, 1979, Table 3), the geothermal potential of the larger, cooler springs is much higher.

Los Alamos National Laboratory, the leader in the development of hot dry rock resources (Resource IV), predicts large such potential resources in the East. At any given depth, temperatures in hot dry rock in the East will be lower than those in the West. The range of temperatures to be expected in the East can be estimated from Fig. A-5. Of particular relevance to the development of a hot dry rock resource in the eastern United States is the physical significance of the linear relation between heat flow and heat generation. If the slope, D, of the linear relation is directly and simply related to a thickness parameter (Costain and Glover, 1980), then thickness of granite and prediction of subsurface temperature in a hot dry rock environment can be made with a high degree of confidence. The validity of this interpretation of the meaning of D could be constrained by reflection seismic data.

Several kinds of geophysical data have been used by us in our targeting strategy, the most important of which are heat flow determinations used to confirm coincidence of high heat flow and low thermal conductivity; these are the characteristics of the radiogenic model. We have also made extensive use of gravity data in our targeting strategy. Because granite usually is less dense than the country rocks into which it has been emplaced, granite occurrences are commonly revealed by negative Bouguer gravity anomalies.

One of the principal objectives of the geothermal program at VPI&SU has been to locate and study uranium- and thorium-bearing heat-producing granites in the Piedmont (Speer and others, 1980), and to predict the occurrence of such granites beneath the wedge-shaped body of chiefly unconsolidated sediments beneath the Atlantic Coastal Plain. Thickness can reach 3 km. During 1978-79, 49 holes were drilled to a depth of approximately 300 m (1000 ft) on the Atlantic Coastal Plain from New Jersey to North Carolina to determine heat flow. Results from the Coastal Plain have been summarized by Lambiase et al. (1980).

The Portsmouth, Virginia, gravity anomaly (Fig. A-6) is an excellent example of a negative gravity anomaly over a confirmed (by drilling) concealed heat-producing granite beneath 600 m of sediments. The geothermal gradient in the hole over the gravity anomaly is about 42°C/km; the gradient is 27°C/km in a hole drilled nearby (12 km) but off the anomaly in the same sequence of sediments. The heat flow over the granite is about 79 mW/m^2. This is excellent confirmation of the radiogenic pluton model.

One promising area for geothermal development discovered to date in the northern Atlantic Coastal Plain is on the Eastern Shore between Crisfield in southern Maryland and Oak Hall in northern Virginia. A deep hole was drilled at Crisfield, Maryland, because of the known high geothermal gradients there and the moderate depth-to-basement. Upon completion on the Crisfield well, it was discovered that the "basement" seismic reflector marked the top of a poorly known 75-m-thick (locally) indurated, high velocity section of Coastal Plain sediments, and that crystalline basement was at the base of this indurated sequence at a depth of 1.36 km. Temperature at the top of crystalline basement was found to be approximately 58°C. The temperature predicted at the base of the Coastal Plain sediments at Crisfield was about 16% less than the measured temperature because of the uncertainty in estimating the thermal conductivity of Coastal Plain sediments in the lower 78% of the sedimentary sequence.

Three zones in the Crisfield hole were pump tested. Zone No. 1 was perforated between 1262 m and 1285 m. The temperature of the water flowing from the perforated zone was 57.2°C. Water pumped from Zone No. 2 (1187-1227 m) for 48 hours at an average rate of 119 gpm produced a head drawdown of 84 m. The temperature of water at the level of perforation was 56°C and at the surface the discharge temperature was 51°C. Zone No. 3 (1155-1170 m) produced an averaged discharge of 32 gpm for 36 hours, resulting in a static drawdown of 30 m. Downhole water temperature was 54°C and surface discharge temperature reached 35°C.

Limited hydrologic and heat flow data now available make it possible to estimate the thermal lifetime of a geothermal resource (the radiogenic model) beneath the Atlantic Coastal Plain. Laczniak (1980) modeled the response of a leaky aquifer system to a pumping plus injection well (a single dipole) using

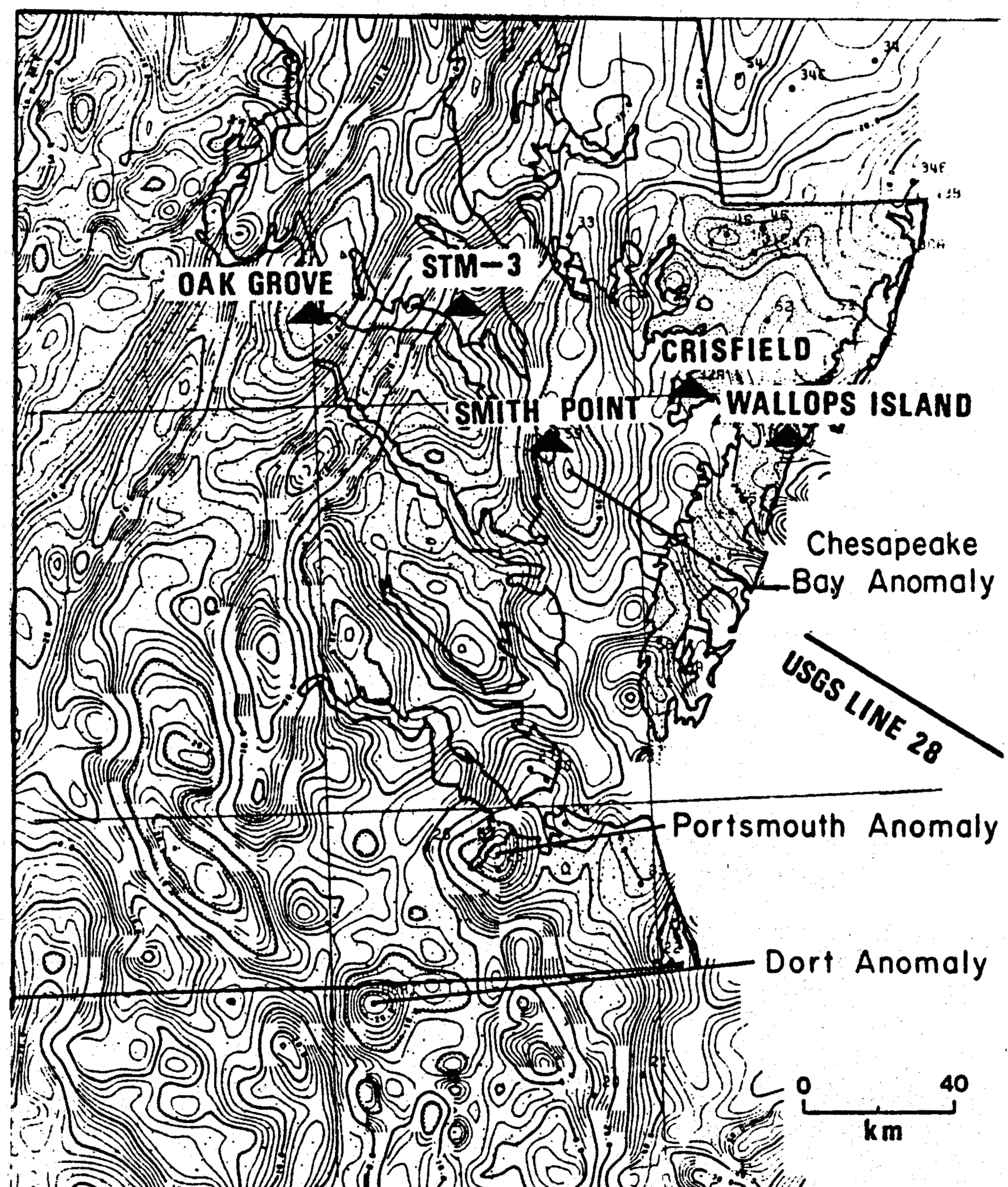

Fig. A-6.
Map showing locations of seismic data in Virginia (Smith Point and Portsmouth).

the integrated finite-difference method. The model was run for a simulated period of 15 years or until steady-state thermal and fluid flow was reached. A doublet system (dipole) with direct injection back into the reservoir was shown to be a feasible method of extracting heat from the low-temperature, liquid-dominated geothermal systems of the Atlantic Coastal Plain.

Important conclusions of Laczniak's study were: a) direct injection back into the reservoir may be necessary to maintain sufficient fluid pressure at the production well for systems with a low permeability; b) temperature distribution within the system is only slightly affected by changes in permeability in the range 10-100 md (millidarcies); c) resting the system for periods of 6 months does not result in a significant recovery; d) a doublet system with thermal and hydrologic conditions similar to those encountered at Crisfield, Maryland, a well spacing of 1000 m, a permeability of 100 md, and a pumping-injection stress of 500 gpm (injection temperature 44°C) could produce 5.5 million Btu's per hour over a period greater than 15 years.

In conclusion, geothermal energy may be an important resource for the eastern United States. Three resource types (the radiogenic model, normal geothermal gradient resources, and hot springs) appear to be favorable for immediate development. Predictions about the thermal longevity of the eastern geothermal resource are favorable.

References

Birch, F., (1954), Heat from radioactivity. In Nuclear Geology, H. Faul, ed., John Wiley and Sons, New York, pp. 148-174.

Birch, F., R. F. Roy, and E. R. Decker, (1968), Heat flow and thermal history in New England and New York. In Studies of Appalachian Geology, E-an Zen, W. S. White, J. B. Hadley, and J. B. Thompson, Jr., eds., Interscience, New York, pp. 437-451.

Costain, J. K., L. Glover, III, and A. K. Sinha, (1980), Low-temperature geothermal resources in the eastern United States. EOS Transactions: Amer. Geophys. Union, 61, no. 1.

Costain, J. K. and L. Glover, III, (1980), Heat flow in granites -- Implications for crustal structure in the Appalachians. In The Caledonides in the U.S.A., D. R. Wones, ed., IGCP, Dept. of Geol. Sci., VPI&SU, Blacksburg, Virginia.

Geiser, P. A., (1976), Structural mapping in the Warm Springs Anticline, northwestern Virginia. In Evaluation and targeting of geothermal energy resources in the southeastern United States, Progress Reports VPI&SU-2, prepared for the Department of Energy under Contract E-(40-1)-5103, pp. 116-164.

Hobba, W. A., Jr., J. C. Chemerys, D. W. Fisher, and F. J. Pearson, Jr., (1979), Geochemical and hydrologic data for wells and springs in thermal-spring areas of the Appalachians. U.S. Geological Survey Water-Resources Investigations Report 77-25, 36 pp.

Lachenbruch, A. H., (1968), Preliminary geothermal model for the Sierra Nevada. Journ. Geophys. Res., 73, 6977-6989.

Laczniak, R. J., (1980), Analysis of the relationship between energy output and well spacing in a typical Atlantic Coastal Plain geothermal doublet system. Unpubl. M.S. Thesis, VPI&SU, Blacksburg, Virginia.

Lambiase, J. J., S. S. Dashevsky, J. K. Costain, and R. J. Gleason, (1980), Geothermal resource potential on the northern Atlantic Coastal Plain, Geology, 8, pp. 447-449.

Muffler, L. J. P., ed., Assessment of geothermal resources of the United States--1978. U.S. Geological Survey Circular 790, 163 pp. (1979).

Muffler, L. J. P. and R. Cataldi, (1979), Methods for regional assessment of geothermal resources. Geothermics, v. 7, no. 2-4.

Perry, L. D., J. K. Costain, and P. A. Geiser, (1979), Heat flow in western Virginia and a model for the origin of thermal springs in the folded Appalachians, J. Geophys. Res.

Roy, R. F., D. D. Blackwell, and F. Birch, (1968), Heat generation of plutonic rocks and continental heat flow provinces. Earth Planet. Sci. Letters, v. 5, 1-12.

Sammel, E. A., Occurrence of low-temperature geothermal waters in the United States. In Assessment of Geothermal Resources of the United States-1978, L. J. P. Muffler, ed., U.S. Geological Survey Circular 790 (1979).

Speer, J. A., S. W. Becker, and S. S. Farrar, (1980), Field relations and petrology of the postmetamorphic, coarse-grained granitoids and associated rocks of the southern Appalachian Piedmont. In The Caledonides in the U.S.A. IGCP Project 27: Caledonide Orogen, Dept. of Geol. Sci., VPI&SU, Blacksburg, Virginia.

White, D. E. and D. L. Williams, eds., (1975), Assessment of geothermal resources of the United States--1975. U.S. Geological Survey Circular 726, 155 pp.

MAGNETOTELLURICS APPLIED TO HOT DRY ROCK GEOTHERMAL EXPLORATION
IN ARIZONA AND NEW MEXICO

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SUMMARY

Magnetotellurics (MT) is an electrical geophysical prospecting technique first developed in 1952 and used primarily in minerals, geothermal, and oil exploration. The technique has also been used to a much more limited extent in solid earth geophysical investigations of the crust and upper mantle. Traditionally, the MT technique has been plagued with many difficult technical problems in all aspects of the technique: experiment design, field procedures, data acquisition, data reduction and analysis, and data interpretation. Recently the MT technique has undergone a revolution in which most of the major difficulties have been overcome. This revolution is still going on, and today we are capable of collecting excellent quality MT earth response functions. The thrust of MT research now lies in the realm of data interpretation.

During the past three years, Los Alamos National Laboratory has conducted a regional MT survey of Arizona and New Mexico for the Hot Dry Rock (HDR) Geothermal Program. The survey consists of over 200 deep MT soundings along several long profiles with sounding spacings of 15 to 20 km (Fig. A-7). The MT lines are located in areas where other geophysical and geologic studies indicate local and regional areas of tectonic and geothermal interest, hot dry rock in particular, such as tectonic province boundaries or late Cenozoic volcanic regions. The MT study is aimed at mapping the depth to the pervasive deep electrical conductor within the crust and/or upper mantle over a large region and then attempting to correlate this depth with terrestrial heat flow, depth-to-Curie point measurements, regional tectonics and local geology. To date, all data have been collected and processed and are in the modeling and interpretation stage. With the exception of the first 56 sites, data from all the remaining sites have been collected using the remote reference MT noise reduction technique.

The locations of the MT profiles for this study (Fig. A-7) and some of the more important preliminary observations of the data are as follows:

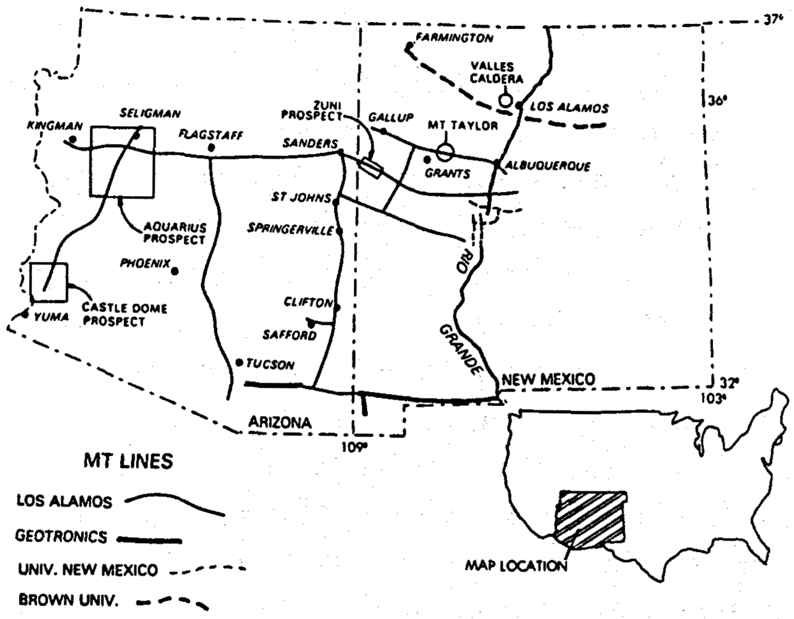

Fig. A-7.
Map showing locations of magnetotelluric profiles in Arizona and New Mexico.

1. A north-south line with 17 sites runs from Yuma in southwest Arizona to Seligman, Arizona, concentrating on the Aquarius and Castle Dome HDR geothermal prospects and traversing the Colorado Plateau/Basin and Range Province boundary. The Castle Dome area coincides with a large amplitude gravity low and with a 70°C/km temperature gradient measured in the center. A caldera, not indicated on the published geologic maps, occurs in the same area. Analysis of the MT data suggests the presence of magma at shallow depths. The Aquarius area is associated with high heat flow, shallow Curie depth, a gravity low, and is associated with a shallow depth to the crustal electrical conductive zone. The Date Creek basin, just south of the Aquarius area, is also associated with a shallow crustal conductor, not as shallow or as conductive as the Aquarius anomaly. The observations are very exciting because they appear to correlate with a very recent migration of the Colorado Plateau boundary from the Date Creek basin to the Aquarius region suggested in a study being conducted by the U.S. Geological Survey (USGS).

2. There are 25 sites along a north-south profile in central Arizona from Tucson northward through Phoenix to Flagstaff, traversing the Colorado Plateau/Basin and Range boundary. The area around Tucson has high heat flow, greater than 104 mW/m^2. Chemical geothermometry measurements also indicate

heat flow greater than 104 mW/m^2 to the northeast of Phoenix. There are geothermal gradients greater than 36°C/km to the southeast of Phoenix. Preliminary observations of the MT data indicate that alternately conductive and resistive layers exist within the crust between Phoenix and Tucson. This observation is intriguing because extensive geophysical surveys performed by oil companies at about the same time as our data were collected show that the western Laramide overthrust passes through this region. Further analysis of the data has proven difficult because of large three-dimensional effects and the large MT site spacing. North of Phoenix, a very shallow, very conductive crustal anomaly is associated with the rim of the Colorado Plateau. This observation, coupled with the MT observation in the Aquarius area and geophysical interpretations across the Colorado Plateau boundary in Utah, provide important constraints on the genesis of the Colorado Plateau. These data sets suggest that the Colorado Plateau boundary is associated with a passive rift system that would impede the propagation of stress across the boundary. Such a passive rift system was hypothesized by Eaton. If the rift system exists, it will provide an important constraint on our models for formation of the Colorado Plateau and Rio Grande rift.

3. Twenty-five sites are along a north-south line starting in the Chiracahua Mountains in southeast Arizona passing through the thermally anomalous Safford-Clifton region, through the Datil-Mogollon volcanics, over the Colorado Plateau boundary, across the northeast-trending Jemez volcanic zone at Springerville, and then to Sanders, Arizona. The Jemez volcanic zone is interpreted to pass through Springerville, Mount Taylor, and the Valles Caldera. These data have not yet been studied.

4. An east-west line consisting of 10 sites runs from St. Johns, Arizona, crossing the Jemez zone and the Plains of San Augustin to Magdalena, New Mexico, where it connects with an MT study of the Rio Grande rift conducted by Jiracek and others. Analysis indicates that the Jemez zone is associated with a shallow conductor suggesting magma at depth and that the Plains of San Augustin may also be associated with magma in the mid-crust. Unlike other conductive anomalies observed in this study, the anomaly beneath the Plains of San Augustin does not correlate with surface heat flow measurements. Elston suggests that the San Augustin basin is a bifurcation of the Rio Grande rift. If this is the case, the existence of a recently developed

magma chamber similar to the one recently discovered in the Albuquerque-Belen basin could account for the discrepancy in the two data sets.

5. The longest MT profile consists of 36 sites from Torreon, New Mexico, to Kingman in western Arizona, traversing the Rio Grande rift and the Jemez zone, passing through Flagstaff, Arizona, and the Aquarius region. This profile passes through the Zuni HDR prospect where a detailed MT/AMT survey consisting of 119 AMT stations and 25 MT stations has been completed. Results indicate that the Jemez zone is a structural flaw associated with magma conduits that penetrate the entire thickness of the lithosphere. Observations of the data from the long profile indicate (a) that the MT soundings have sensed a magma body beneath the San Francisco Peaks area near Flagstaff, and (b) that the depth to the deep electrical conductor along the profile correlates with surface heat flow, the thickness of the lithosphere, and an inverse correlation has been noted with Bouguer gravity.

6. There are 15 sites along an east-west profile from Gallup to Albuquerque, New Mexico, that passes over Mount Taylor, a volcanic field of the Jemez zone. Again, the data strongly indicate that the Jemez zone is associated with a shallow electrical conductor, probably caused by magma at depth. The observation from all MT profiles across the Jemez zone that the zone is associated with a crustal flaw penetrating the lithosphere correlates with (a) preliminary results of a teleseismic P-wave delay study that indicates the zone is associated with a low seismic velocity zone from 15 to 140-km depth; (b) elevated heat flow along the zone; and (c) the observation by numerous workers that the zone is associated with a Precambrian age boundary. Based on the MT data and extensive integration of other geophysical and geologic data, I suggested that the Colorado Plateau southeastern boundary is presently coincident with the Jemez volcanic zone and that a recent migration of the Colorado Plateau boundary to the northwest has occurred. Other workers have since found structural evidence to support these findings.

7. Five sites have been occupied in southeast Arizona connecting two nonproprietary MT surveys consisting of 40 sites occupied by Geotronics Corp., resulting in a station distribution that is a continuous east-west profile from El Paso, Texas, to Tucson, Arizona, along the 32°N latitude. These MT data have not been studied yet.

8. This MT study integrates with a telluric-magnetotelluric survey in the Jemez Mountains of northern New Mexico to characterize the geothermal

system of the Valles Caldera and with a regional northwest-trending MT survey. These surveys were conducted by Hermance for the USGS and Los Alamos National Laboratory.

Based on the results obtained so far, several general conclusions can be made. No single geophysical technique is a panacea for geothermal exploration, hot dry rock in particular. But, because MT is sensitive to the crustal state, it is an excellent exploration tool when used in combination with geologic and other geophysical techniques. The depth of the deep electrical conductor obtained by the MT method in general correlates with the expected crustal thermal regime as predicted by terrestrial heat flow, depth to Curie, regional tectonics, and/or local geology. In this study, mapped crustal electrical conductivity upwellings in otherwise resistive crustal rock correspond with known or suspected thermally anomalous areas. These conductivity upwellings fall into two basic categories. The first contains a resistive cap rock ($\geq$1000 Ωm) and appears to be associated with local thermal features, e.g., Castle Dome anomaly. Because the cap rock is resistive, suggesting impermeable upper crust, local ground-water percolation is not a likely mechanism for creating the high conductivity anomaly. Such regions, when coincident with other thermal indicators (e.g., late volcanic activity and high heat flow), may be good hot dry rock targets. The second type contains a moderately conductive cap rock (<100 Ωm) and appears to be associated with zones of tectonic extension, e.g., Colorado Plateau boundary. These regions are probably associated with deeply circulating ground water that causes increased conductivity. Because these regimes are usually associated with elevated thermal regions, the anomalously high electrical conductivity beneath the more resistive cap may be due to free water in the presence of elevated temperature and/or partial melt. These regions may also be important hot dry rock resource areas, but more care must be taken to evaluate the cause of the conductive anomalies.

INTERPRETATION OF MAGNETOTELLURIC SOUNDINGS FOR HOT DRY ROCK PROSPECTING

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Electrically conductive intracrustal zones have been detected by magnetotelluric (MT) soundings in tectonically active areas as well as in stable crustal environments throughout the world. Many researchers are convinced that the layers are due to crustal magma, particularly in active regions. If this association is valid, the detection of such layers at shallow depths would signal a source of heat that could produce a viable hot dry rock target. The successful analysis of magnetotelluric soundings in hot dry rock exploration must, however, consider other possible sources of conductive zones in the earth's crust. For example, pore water and thermally activated electronic solid-state semiconduction enhanced by crystal-charged defects, impurities, volatiles, metamorphism, and ductile flow mechanisms may be important. Also, purely geometrical effects can be mistaken for conductive layers at depth.

Two-dimensional modeling of recent magnetotelluric soundings in the central Rio Grande rift (Jiracek et al., 1982) has confirmed the existence of conductive zones at depths of 10 km or less. Some soundings are located over a region where contemporaneous magma bodies are well-defined at shallow and intermediate crustal levels by seismic observations. Surprisingly, however, the crust is more conductive by at least an order of magnitude where the magma is <u>not</u> detected compared to where it has been confirmed. To explain this result, it is first suggested that a conductive horizon occurs in the crust where an impermeable, ductile cap traps pore fluids beneath. This concept of the crust follows the geologic model presented by Eaton (1980) for the Basin and Range province, therefore, it may have wide applicability in the western United States. Fig. A-8 summarizes the model.

Ductile flow mechanisms are thermally activated processes, which involve charged defects, lattice dislocations, or atomic diffusion, all of which enhance solid-state electrical conduction. The hypothesized ductile layer

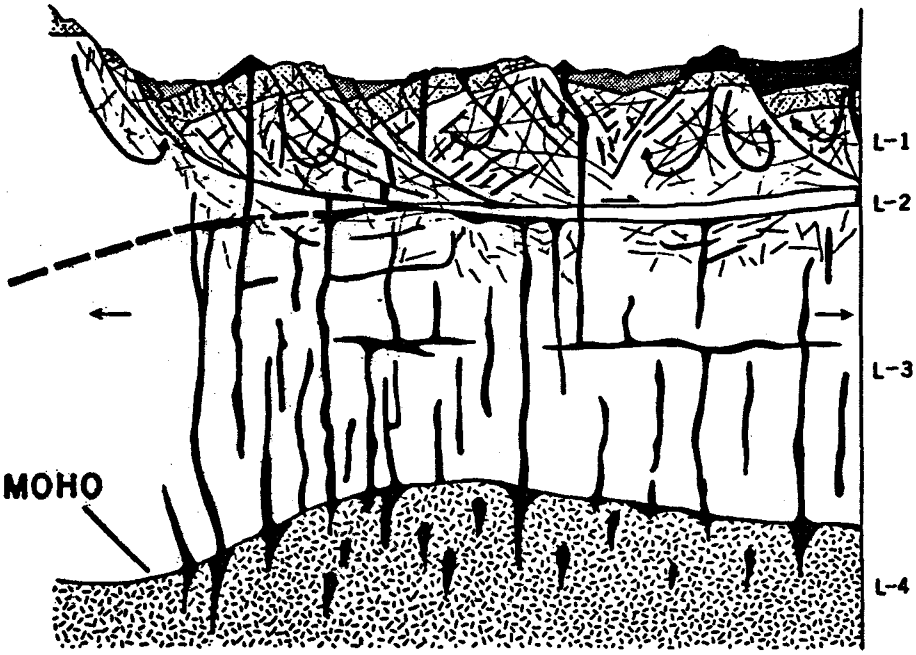

Fig. A-8.
Interpretive model of possible basin and range (or rift) structure (simplified, schematic, and not to scale). Crust is composed of three layers. L-1 is brittle, fault-fragmented surface layer 8-15 km thick. Base of L-1 generally marks the maximum depth of earthquake foci. L-2 is ductile intermediate layer, 0-3 km thick. L-3 is the lower crust, 10-20 km thick, composed of basement rocks on top, grading downward from granitic to mafic in composition. The uppermost part of L-3 may contain high-pressure, high-temperature pore fluids in a system capped by impermeable layer, L-2. L-4 is the lithospheric mantle, ultramafic in composition. Bleb-like bodies of rising magma in L-4 intrude the crustal layers as dikes and sills (indicated by solid black). Ductile crustal layer, L-2, may mark the top of an electrically conductive zone, which extends into layer L-3 when highly conductive pore fluids are trapped. Magma intrusion through the ductile cap may release these pore fluids thus reducing the overall conductivity of the sequence. Schematic diagram after Eaton, 1980.

(L-2, Fig. A-8) would, therefore, be perhaps an order of magnitude more conductive (~100's ohm-m) than the dry, brittle crust above it (L-1, Fig. A-8). A zone of trapped pore fluids (top of L-3, Fig. A-8) would be even more conductive by about another order of magnitude (~10 ohm-m). Mineral dehydration at greater depth due to an enhanced thermal gradient or magma injection could provide such fluids.

If active magma injection destroyed the integrity of the ductile cap, trapped fluids would escape resulting in an overall decrease in conductivity.

The final electrical signature with such a dynamic concept would depend on the thermal gradient, the relative impermeability of the cap, the extent of pore fluids beneath, and the amount (and frequency) of magma intrusion. The temporal and spatial distribution of earthquake foci in the western United States supports the existence of a ductile layer at 5 to 15-km depth and the hypothesis of magma injection.

The aforementioned considerations result in a more resistive crust despite the presence of magma bodies; these bodies would have to be a minor constituent of the crust, otherwise the effects of a highly conductive magma would dominate.

The depth at which a ductile zone would form in the crust is dependent on pressure, temperature, composition and tectonic stress. Since temperature would likely be the major variable in a given geologic province, the depth of a conductive layer caused by ductility would provide a measure of the thermal gradient. So, even if crustal conductive zones are reflecting the depth of ductility rather than crustal melt, they may still provide a very useful geothermal indicator. As previously mentioned, the ductile layer would not be as conductive as a zone of high-pressure pore fluids or of a significant concentration of magma. These latter two possibilities would not be separable by magnetotelluric data alone; however, MT results combined with active and passive seismic reflection measurements such as those performed in the central Rio Grande rift (Brown et al., 1980) should be diagnostic.

References

Brown, L.D., Chapin, C.E., Sanford, A.R., Kaufman, S. and Oliver, J., 1980. Deep structure of the Rio Grande rift from seismic reflection profiling. J. Geophys. Res., 85:4773-4800.

Eaton, G.P., 1980. Geophysical and geological characteristics of the crust of the Basin and Range province. In: Studies in Geophysics-Continental Tectonics, Nat. Acad. Sci., Washington D.C., pp 96-113.

Jiracek, G.R., Gustafson, E.P. and Mitchell, P.S., 1982. Enhanced conductivity in continental rift zones and magnetotelluric grounds for ductile origin in the Rio Grande rift. Submitted to: Proceedings of the Conference on Planetary Rifting, Tectonophysics.

SOME EFFECTS OF TWO-AND THREE-DIMENSIONAL STRUCTURE ON MAGNETOTELLURIC DATA

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Introduction

Magnetotellurics (MT) has found widespread application in the evaluation of geothermal resources. Taking advantage of the potential ability both to determine deep crustal properties and to identify and map shallow hot aquifers and fluid-filled fault systems, MT has been used for both regional and prospect-specific exploration.

Data acquisition instrumentation and processing software have steadily increased in sophistication and reliability. As these aspects of MT mature, more emphasis is being placed on interpretation, in particular on the complicating effects of geologic structure as explorationists consider cases that depart from the simple, plane-layered "Cagniard" earth. Since most, if not virtually all, practical geothermal exploration problems involve a geologic setting that is at least two-dimensional, the concern to workers in the field can be easily understood.

This paper is an interim report, a "progress review" of one informal group actively working on various aspects of MT interpretation in complex areas. The authors, representing an academic institution, a geophysical contractor and an exploration group, bring to the study a wealth of varied experience in both theoretical and applied research.

The objectives of the paper are three-fold. First, the authors wish to share selected preliminary observations with colleagues equally concerned with the subject at hand, since it has become obvious that there are subtle pitfalls in MT interpretation awaiting the unwary. Second, it is desired to suggest approaches to MT survey planning that take into account potential interpretive problems. Lastly, it is hoped that awareness of interpretive problems will lead to increased encouragement and support for researchers in the field.

MT Interpretation, An Overview

Standard MT processing results in the calculation of two orthogonal apparent resistivity-vs-frequency curves at each recording location. If the earth is not plane layered, then the two curves will in general be different, and be aligned (at least in the two-dimensional case) parallel and perpendicular to strike. The goal of an MT interpretation is to correctly identify the subsurface configuration that led to the observed data. This is accomplished through the comparison of field data with that obtained from model calculations, and/or the direct inversion of the field data. The latter technique has become increasingly popular, with the recognition that simple relationships exist whereby each of the apparent resistivity-vs-frequency curves can be inverted to a continuous "intrinsic" resistivity-vs-depth form. These single-curve inversions, however, assume for each curve that the earth is one-dimensional, thus two different resistivity-depth curves may be computed at each location. The interpreter's job at this point is one of determining how, from the two available resistivity-depth curves, to best approximate the actual resistivity-depth relationship.

For geothermal applications, the principal implications of the above are as follows: First, for regional studies investigating the lower crust, the location of the deep conductor (the presumably hot lower crust) is the desired target, and the interpretation of the lower frequencies, and a correct inversion of the low frequency data, is critical. Second, when looking for shallow, hot aquifers an accurate interpretation of the location and geometry of conductive anomalies is the desired result. In both cases, in a non-one-dimensional setting interpretive decisions must be made which, as will be shown, may have a critical effect on the outcome.

Two-Dimensional Considerations

In a one-dimensional setting with resulting isotropic MT data the continuous inversion is an excellent interpretive tool. In particular, if crustal parameters are slowly varying laterally then the interpretation of relative depths can be accurate. In a two-dimensional setting, however, the two inversions (of each of the two orthogonal apparent resistivity curves) will differ. Study of a large number of two-dimensional model calculations and comparison with field results in well-understood geologic settings leads to the following observations:

1. The one "correct" apparent resistivity curve and the resulting inversion, i.e., the data that would be observed and calculated if the stratigraphy directly beneath the site in question extended indefinitely in all directions, in general lies somewhere between the extremes of the two observed curves. It is important to note that this is not necessarily a good assumption in the three-dimensional case.
2. In some cases, such as the common geologic setting of shallow, lateral resistivity variations in otherwise plane-layered stratigraphy, one of the observed resistivity curves may be an excellent approximation to the "correct" curve.
3. In some cases, such as large-scale basin and range faulting, the observed data may be extremely anisotropic and neither curve may approximate the "correct" curve to within as much as an order of magnitude, especially at the lower frequencies.
4. In geologic settings resulting in anisotropic data, low-frequency characteristics of one or both of the resistivity curves may be much more reflective of lateral variations than vertical stratigraphy. Stated more strongly, low frequencies do not necessarily equate totally to deep penetration.
5. When thin, highly conductive strata are present, especially if these terminate, then an accurate determination of depth and extent of the conductor may be difficult, especially if the data are noisy.
6. A qualitative interpretation of widely spaced MT sites is almost always possible even if the data are anisotropic, given a knowledge of the regional geologic framework, the topography and surface geology in the vicinity of the site. The quantitative interpretation of anisotropic MT data becomes credible as data becomes available from multiple sites, and improves as sites are spaced more closely, especially in the vicinity of lateral resistivity variations.

Three-Dimensional Considerations

The study of the effect of three-dimensional structural complexity on MT data has been difficult due to the limited availability of applicable modeling programs and the computation expense involved. Recent advances have improved this picture, and model computations have become available, which have provided interpreters with considerable insight. In addition to model studies, the analysis of field data obtained in the vicinity of well-documented, strongly three-dimensional structures has led to a start towards the understanding of what kinds of data to expect under such circumstances.

The model studies have been directed specifically at problems of interest to regional geothermal exploration. The results indicate that for many simple, geologically common settings with structure involving only the shallow upper crust, MT data can be affected such that both orthogonal resistivity curves yield an anomalously shallow lower crust. Thus, by utilizing standard interpretation techniques, a "crustal upwelling" could be identified in cases where none in fact exists. Of particular concern is the case of a broad, conductive sediment-filled valley, which represents a typical location where a regional MT site might be placed. What is most insidious about this class of problems is that the data at an affected site may appear isotropic; the interpreter received no warning from the MT data itself.

Once the possibility of the effect is recognized, then a regional survey can be designed with a grid of sites. With a knowledge of the topography and the geological framework, even a limited number of sites should be able to yield a credible interpretation.

The field data studies have concentrated on an investigation of the "out-of-limits phase" phenomenon, whereby the phase as well as the amplitude of one of the orthogonal apparent resistivity components appears to behave anomalously. If one- or two-dimensional inversion techniques are used under such circumstances, erroneous resistivity-vs-depth values will almost certainly result. The effect appears to be the result of utilizing data analysis techniques that involve assumptions that are invalid in some three-dimensional situations. It is normally assumed, for example, that the maximum and the minimum resistivity components are orthogonal. If in fact they are not, then the minimum resistivity component may be "contaminated" by a contribution from the maximum component, giving rise to the observed errors. While in most cases the existence of a problem site is self-evident, examination of polar plots of the diagonal as well as off-diagonal apparent resistivities should become part of the interpreter's routine in complex areas.

Concluding Remarks

Magnetotelluric interpretation data is a complex art, even in many cases where the data appear straightforward. The recognition of this complexity is a major step towards the realization of the method's capabilities. The study of two- and three-dimensional models will provide the interpreter with invaluable if not critical insight. Finally and most important, a survey should be planned utilizing this insight, and taking into account all available regional and site-specific information.

DETERMINATION OF DEPTH TO THE CURIE ISOTHERM FROM AEROMAGNETIC DATA

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The basic objective in relating the aeromagnetic field data with the structure of the Curie point isotherm is to compute the lower depth limit of magnetized masses in the earth's crust. Rocks lose their magnetism at the Curie temperature at which ferrimagnetic rocks become paramagnetic, and their ability to produce detectable magnetization disappears. Thus, the deepest level in the crust containing materials with discernible magnetization is generally interpreted as the depth to the Curie point isotherm.

The Curie point is about 580°C for magnetite. With appropriate titanium substitutions, Buddington and Lindsley (1964) calculated an average Curie point ranging betwen 520°C and 560°C for rocks in the deep crust. It is generally believed that the amount of geothermal heatflow should correlate with the Curie depth and thus, in turn, to the crustal magnetic field.

Our main goal is, therefore, to determine the bottom shape of the magnetized crust from a magnetic anomaly map. Since the magnetic anomalies attributable to the bottom geometry are usually quite smaller and have much longer wavelengths than those produced by shallow geological variations, the problem is comparable to searching for a needle in a haystack. Early studies include those by Vacquier and Affleck (1941) and Bhattacharyya and Morley (1965). In both cases, each isolated anomaly was filtered and separately interpreted by the empirical graphic method using a vertical-sided prism.

A more sophisticated method was proposed by Bhattacharyya and Leu (1975a, 1975b). Their method requires an extensive initial filtering of the aeromagnetic data in both regional and short wavelength domains. The filtered data is subsequently divided into a large number of blocks. For each block, a two-dimensional spectrum and its moments are computed and compared with a model of an isolated vertical-sided prism within a block in order to locate the corners of the body. The total amount of computation is tremendous since the method requires a two-dimensional Fourier transform for each block. Applying the method to the Yellowstone National Park area, they produced the Curie isotherm map well-correlated with the known geothermal area.

Employing a similar technique, it is essentially impossible to determine Curie depth with any resolution at all by fitting a vertical prism to a single anomaly. The Curie depths they derived could be changed by as much as 10 km without violating the observed data. This conclusion is seemingly in conflict with those of Bhattacharyya and Leu (1975b).

All methods reviewed here are commonly based on the assumption that there exists an isolated magnetic source for each anomaly. Each individual anomaly is assumed to be caused by a single vertical-sided prism (Bhattacharyya and Leu, 1975a, 1975b) or a truncated vertical cone. Such isolated models are apt to generate spurious anomalies, particularly due to their unrealistically well-defined corners and vertical surfaces. These spurious anomalies can induce significant errors in either direct-modeling or spectrum calculation.

Rock formations causing long wavelength magnetic anomalies at a depth close to the Curie point are more likely to have a continuous lateral distribution rather than isolated blocks of well-defined geometrical bodies. A realistic model at this depth should manifest a continuous lateral distribution of magnetic materials having variable thicknesses and susceptibilities.

Fluctuations in long wavelength magnetic anomalies can be attributed to lateral variations either in magnetization strength or in Curie depth. These double uncertainties make the task of simultaneously determining both the magnetizations and the Curie depth very difficult, if not impossible. Similar uncertainties apply to many geophysical modeling theories, e.g., a thin magnetic dike for which the anomaly is the same as long as the product of thickness and susceptibility remains the same. However, it can be shown that the statement is no longer true if the dike has a considerable thickness for which case both the thickness and the susceptibility can be independently determined from observed data (Won, 1981). The present approach is based on the classical Gauss method for solving nonlinear equations (Carbato, 1965; Johnson, 1969; Won, 1981) coupled with Marquardt's inversion method (Marquardt, 1963) to derive continuous crustal thickness and susceptibility profiles from regional magnetic data.

Figure A-9 shows the model that is used for inverting magnetic data. The model consists of laminated thick vertical prisms having flat top surfaces and linearly connected inclined bottom surfaces. The magnetic susceptibility below the lower boundary is assumed to be zero so that the bottom geometry represents the Curie isotherm topography. Although data will be confined within the laminated block region, two semi-infinite slabs are added on either side in order to reduce the edge effects of the first and last blocks. The unknown parameters to be determined are the depth (h's) at each nodal point and the magnetic susceptibility (k's) of each prismatic body.

The model is two-dimensional with an arbitrary strike angle with respect to the magnetic north. Data are assumed to be obtained at a constant altitude along a traverse perpendicular to the strike. Since the method uses total field magnetic data, there is no need for reducing the data to the polar anomalies. The magnetic anomaly generated by a single vertical block having a flat top and an inclined bottom can be derived by analytically combining two inclined dikes. By summing up these individual blocks, we can compute total field for any given set of blocks having variable depths and susceptibilities.

Techniques for determining unknown parameters of a nonlinear function involve iteratively correcting currently assumed parameters by differential amounts, thereby minimizing the rms error between the theoretical prediction and the observed data. Two predominant techniques of determining the correction amounts are Gauss' method and the gradient, or the steepest descent method. Marquardt's method combines these methods by controlling the amounts of differential correction to insure both the convergence and speed.

Using the geometrical model and the inversion technique, we analyzed aeromagnetic data of the Yellowstone Park, Wyoming (Fig. A-10). The digitized data were first low-pass filtered at a 10-km wavelength. A total of 12 east-west profiles evenly distributed in the area were then subjected to the inversion process to derive simultaneously the depth and susceptibility profiles. Figure A-11 shows the estimated Curie depth and Fig. A-12 the susceptibility structure for the entire area. A cursory check with available surface geological map of the area shows the results are reasonably correlated with local geology. Since the results derived here represent the thickness of the entire magnetized crust and its average susceptibility, it is rather difficult to compare with the available superficial geological information. The main consolation is, however, that, for the entire profiles, the rms difference between the field data and model data is mostly less than two gammas, an excellent match for the geologically complex area.

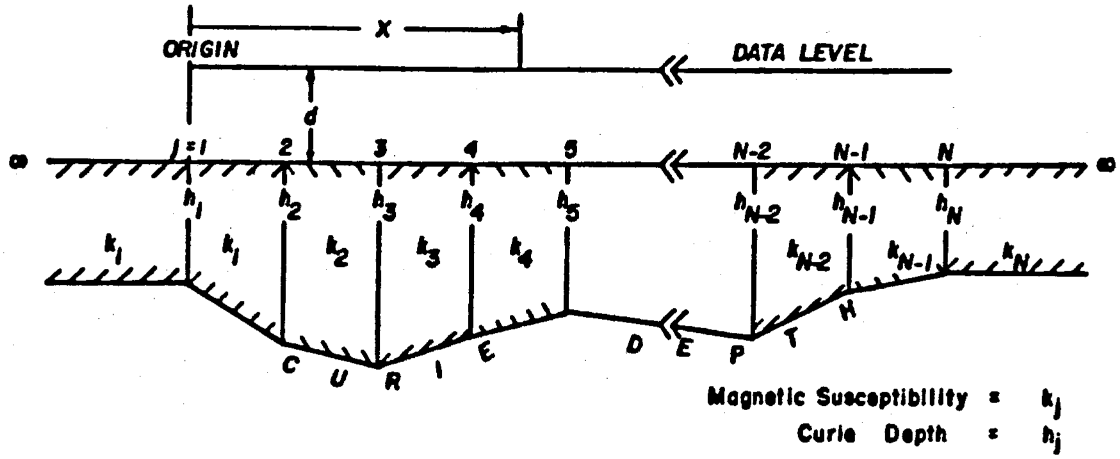

Fig. A-9.
Mathematical model of the Curie depth.

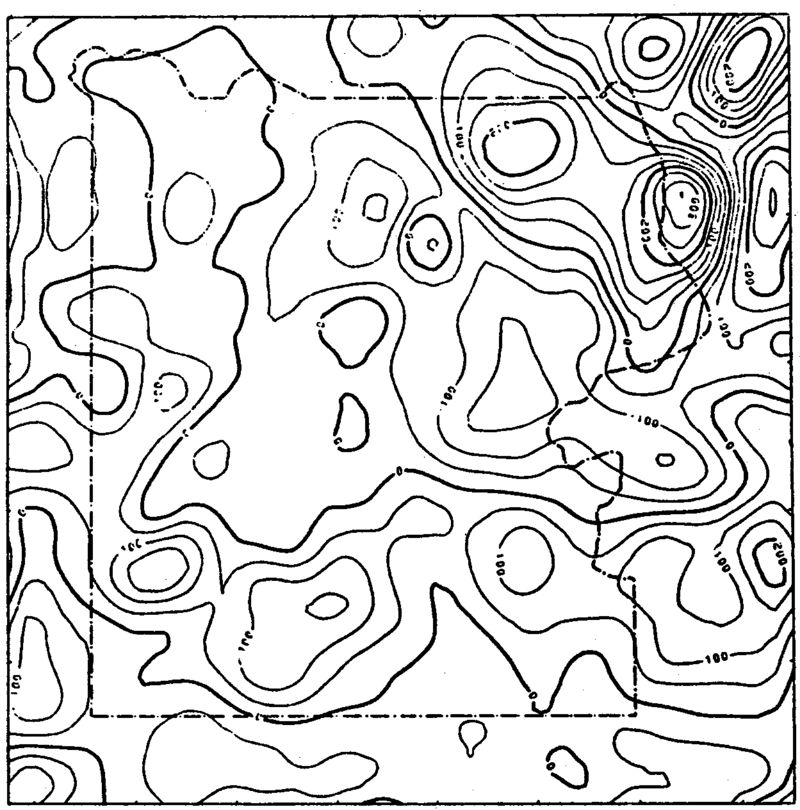

Fig. A-10.
Filtered aeromagnetic map at a 50 gamma contour interval. Broken line shows the boundary of the Yellowstone Park.

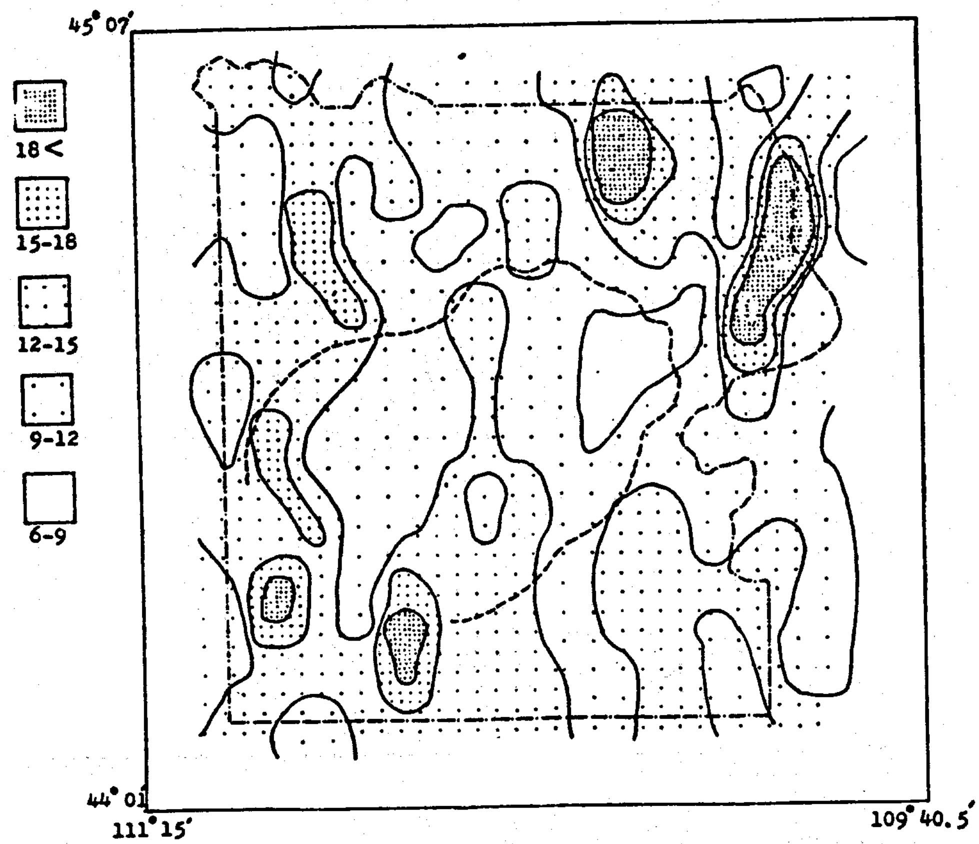

Fig. A-11.

Depth to the Curie isotherm derived from the aeromagnetic profiles: contour interval is 3 km.

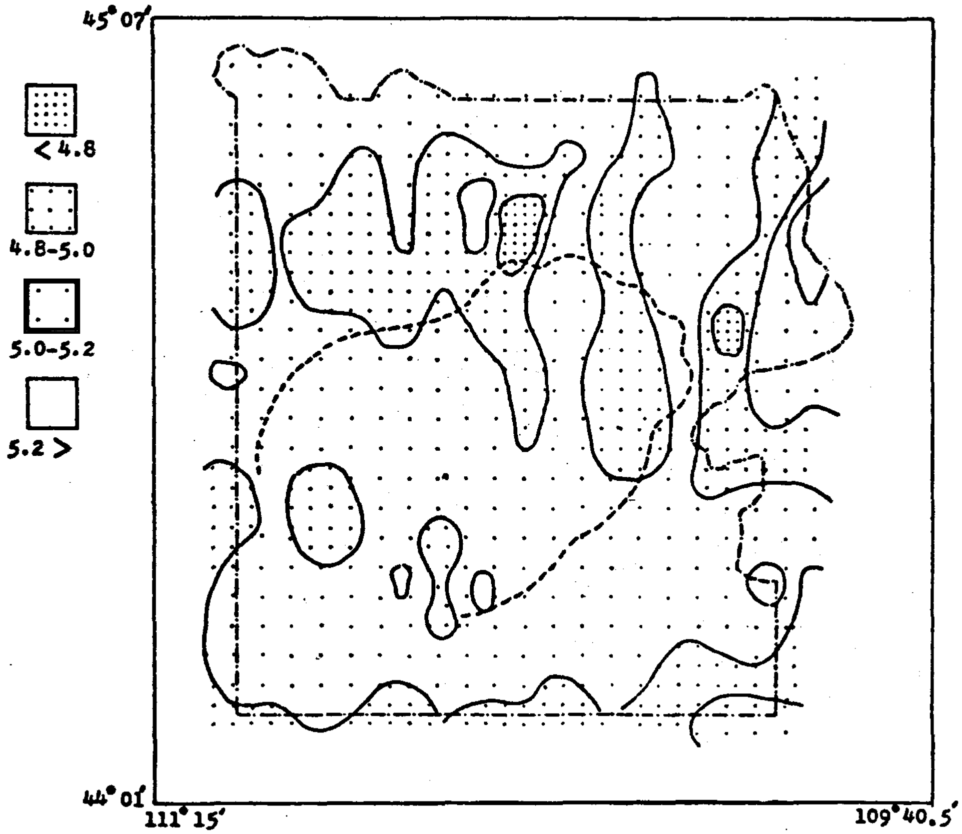

Fig. A-12.
Magnetic susceptibility map derived from the aeromagnetic profiles: contour interval is 0.0002 emu.

References

Bhattacharyya, B.K., and Leu, L.K., 1975a, Spectral analysis of gravity and magnetic anomalies due to two-dimensional structures, Geophysics, V. 40, pp. 993-1013.

Bhattacharyya, B.K., and Leu, L.K., 1975b, Analysis of magnetic anomalies over Yellowstone National Park: Mapping of Curie point isothermal surface for geothermal reconnaissance, J. Geophys. Res. 80, 30, pp. 4461-4465.

Bhattacharyya, B.K., Morley, L.W., 1965, The lineation of deep crustal magnetic bodies from total field aeromagnetic anomalies, J. Geomag. Geoelect., 17, pp. 237-252.

Buddington, A.F., and Lindsley, D.H., 1964, Iron-titanium oxide minerals and synthetic equivalents: J. Petrology, v. 6, pp. 310-357.

Carbato, C.E., 1965, A least-squares procedure for gravity interpretation, Geophysics, 30, pp. 228-233.

Johnson, W.W., 1969, A least-squares method of interpreting magnetic anomalies caused by two-dimensional structures, Geophysics, 34, pp. 65-74.

Marquardt, D.V., 1963, An algorithm for least-squares estimation of nonlinear parameters, J. Soc. Indust. Appe. Math., v. 11, 2, pp. 431-441.

Vacquier, V., Affleck, J., 1941, A computation of the average depth to the bottom of the earth's magnetic crust based on a statistical study of local magnetic anomalies, Trans., Am. Geophys. Union, pp. 446-450.

Won, I.J., 1981, Application of Gauss' method to magnetic anomalies of dipping dikes, Geophysics, 46, 2, pp. 211-215.

3-D SEISMIC VELOCITY ANOMALIES IN THE CRUST AND UPPER MANTLE ASSOCIATED WITH GEOTHERMAL AREAS OF THE WESTERN UNITED STATES

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I shall review the 3-D seismic velocity structures determined by seismic arrays operated in the western United States, with special reference to anomalies associated with known geothermal areas.

From the teleseismic P-time residual data obtained at the nation-wide network, large-scale anomalies were identified under the western United States by Romanowicz, who interpreted them as the seismic image of the window in the Farallon plate proposed by Dickinson and Snyder. The window was created because the San Andreas transform boundary cannot supply lithospheric material behind the subducting Farallon plate. Dickinson and Snyder explain the recent history of volcanism and uplift in the western United States by the upwelling of hot material from the asthenosphere through the window.

Cockerham and Ellsworth used the data from the dense Central California network and discovered a remarkable "inclined low-velocity zone" dipping eastward from the San Andreas, which could be identified as the Dickinson-Snyder window filled with soft ductile material.

Geothermal areas within the surface projection of the Dickinson-Snyder window show distinct low-velocity bodies in the crust and upper mantle, which apparently have deformed shapes. Examples are the Coso, Roosevelt Hot Springs, and Geysers Clear Lake areas studied by Iyer and his colleagues.

Under the Yellowstone caldera, which are located outside the window, the low-velocity body appears to be upright and undeformed.

Under the Cascades volcanoes, also located outside the window, Iyer and his colleagues have not found any pronounced low-velocity body.

Whatever is causing the difference in velocity structure between geothermal areas inside and outside the Dickinson-Snyder window, the consistent occurrence of low-velocity bodies in the crust and upper mantle immediately beneath geothermal areas within the window may be used as a guide for finding new geothermal areas, at least within the window area.

FENTON HILL SITE SELECTION AND EVALUATION: A CASE HISTORY

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Introduction

Continuing technical success in the development of techniques for hot dry rock (HDR) energy extraction justifies review of the Fenton Hill "case history." This history begins with the original site selection criteria, proceeds through the compilation of existing data and collection of new data to the evaluation of methods and results and finally to the application of these results to the search for new sites. Reviewed in perspective the case history shows that the original site selection criteria were correct. It also shows that the site selection techniques were effective in determining if the criteria were met at a particular site. Based on the Fenton Hill results, a generalized site selection and assessment plan can be proposed.

Site Selection

After the general concept for extracting geothermal energy from HDR was conceived (Robinson et al., 1971), a suitable site for developing and testing the extraction techniques was needed. The most obvious criteria for the site were that it should be underlain by very low permeability rock at high temperatures. To reduce drilling costs, high geothermal gradients were sought. Low seismicity was also specified as a criterion because of the effects of seismicity on permeability and because of earthquake hazards. Logistic and environmental concerns, although important, will not be discussed here.

The original geothermal group at Los Alamos was fortunate that the Laboratory is located within the Jemez Mountains, a region of known late-Cenozoic volcanism. The close proximity of a young silicic caldera alleviated many logistic problems and prior geologic interest in the area provided considerable evidence of a high-temperature volcanic heat source. Of primary importance was the excellent geologic map of Smith, Bailey and Ross (1970), which detailed the volcanic stratigraphy, structure, and some thermal manifestations. Adequate geochronology was available indicating volcanism continuing from about 10 m.y. to 0.04 m.y. (Doell et al., 1968). Direct evidence for geothermal resources within the Valles Caldera was also provided by newspaper accounts of successful well drilling by a private company. The seismicity was known to be low in the area minimizing risks of inducing earthquakes during later hydraulic fracturing and suggesting the probability of low secondary permeability. Some knowledge of basement structures was obtained from unpublished gravity and aeromagnetic data provided by Lin Cordell of the U.S. Geological Survey. Both Cordell and Roy Bailey of the U.S.G.S. met with Laboratory staff to assist in site selection.

Several small investigations were initiated to narrow down the choices for a site within the Jemez Mountains. Bailey and Cordell had suggested the western flank of the Valles Caldera to minimize the effects of faults related to the Rio Grande rift and the resurgent dome within the Valles Caldera. To confirm that elevated subsurface temperatures were present outside the caldera, Marshall Reiter of New Mexico Institute of Mining and Technology and Los Alamos staff drilled and logged seven shallow and four intermediate depth gradient holes on the southern and western flanks of the caldera. Heat flow values of about 230 mW/m^2 were measured in the deeper holes on the western flank.

An aerial photographic fault investigation was initiated to assist in evaluating the secondary permeability. A preliminary version of the fault study by Slemmons (1975) indicted that the Barley Canyon-Fenton Hill region of the Jemez Plateau was seismically quiet and within a large intact fault block. Concurrently, a slim hole (GT-1) was drilled in Barley Canyon to evaluate heat flow and the permeability of potential basement reservoir rocks. This well reached a total depth of 785 m, 143 m into the Precambrain basement. Because of hydrologic disturbances the geothermal gradient was 129°C/km in permeable Paleozoic rocks and 45°C/km in low permeability Precambrian rocks. Permeability measurements ranged from 5×10^{-8} to 6×10^{-3} darcies. Hydraulic fracturing was also accomplished in GT-1 indicating low permeability.

After evaluation of the results obtained in these studies a new drill site was selected at Fenton Hill. This site was within the same intact fault block as the Barley Canyon site, had about the same heat flow and was better located for logistic and environmemtal reasons.

<u>Phase I System Development and Investigations</u>

The Phase I HDR system was constructed at Fenton Hill using two drill holes - GT-2 and EE-1. Drill hole GT-2 had a total depth of 2.93 km and a bottom-hole temperature of 197°C and EE-1 a total depth of 3.06 km and a bottom-hole temperature of 205.5°C. Cores, cuttings samples, and geophysical logging were used to characterize the basement rocks in which the Phase I system was developed. A metamorphic complex intruded by biotite granodiorite and monzogranite bodies was recognized. Samples of the various lithologies were used for whole-rock chemistry, petrology, geochronology, rock mechanics, rock-water interaction and permeability studies. Results of these studies are given in Laughlin (1981), Brookins et al. (1977), Zartman (1979), Laughlin et al. (in press), Brookins and Laughlin (in press), and Charles and Bayhurst (in press).

The Phase I system was developed entirely within the 385-m-thick biotite granodiorite body. This rock is a very homogeneous igneous rock characterized by high modal biotite and sphene contents and high concentrations of K_2O, TiO_2, and P_2O_5. Although the biotite granodiorite contains fractures, they are almost invariably sealed with a variety of minerals. Calcite, epidote, hematite, chlorite, quartz, clays, feldspars, and sulfides have all been observed as fracture filling minerals. These sealed fractures show spacings of 1 to 8 cm and are variously horizontal, vertical, or steeply dipping. Strontium isotopic studies by Brookins and Laughlin (1976) indicate that the calcite in the fractures was probably derived from adjacent Precambrian rocks and not from overlying limestone.

The results of the geochronological investigations show a history of metamorphism at 1.62 b.y., intrusion of the biotite granodiorite at 1.50 b.y., and intrusion of the monzogranite at 1.44 b.y. (Brookins and Laughlin, in press). These Rb-Sr results as well as the U-Th-Pb results of Zartman (1979) suggest that these systems have remained closed despite present high temperatures. The results of K-Ar dating (Turner and Forbes, 1976), also indicate little movement of the daughter isotope despite temperatures as high as 313°C in EE-2.

While the Phase I was being developed, a number of surface geologic and geophysical investigations were performed to better characterize the Fenton Hill site. In hopes of predicting the orientation of hydraulic fractures, fracture-orientation data were obtained from Precambrian exposures in the Jemez Mountains. In these outcrops the two fracture sets with the greatest frequency trend north-northwest and northeast to east-northeast. These directions are consistent with fractures trending N42°E, N49°E, N52°E, and N25°W in cores from GT-2.

Two shallow seismic reflection surveys were run in the area to refine the knowledge of the structural setting near the drill site. Results were reported by Kintzinger and West (1976) and Kintzinger et al. (1978). Several faults were recognized by these surveys. A prominent NNE striking fault with a SE dip lies immediately west of the drill site, an E-W striking fault with a S dip was detected N of the drill site and a NE striking horst was observed in the Precambrian subsurface N of Barley Canyon. This horst is in part coincident with a gravity high mapped by Cordell (1976).

Electrical resistivity methods were employed by Jiracek (1975) to characterize the Fenton Hill site. Schlumberger soundings and the roving dipole and dipole-dipole methods were used. Several relatively shallow conductive zones were recognized. The outermost ring fault was particularly well defined, probably because of hot water moving up along it.

Hermance (1979) was funded by Los Alamos and the U.S.G.S. to conduct a telluric-magnetotelluric survey of the Jemez Mountains and northern New Mexico. A total of 30 stations was run in the Jemez Mountains; 17 stations were occupied on the Baca Grant with permission from Union Oil Company. Hermance found that his results within the Jemez Mountains were very similar to those from the Rio Grande ift. He presented evidence for a partial melt accumulation at a depth of 15 km.

Because of the limited number of cores available, additional evidence was sought for the nature of the basement rocks. Eichelberger and Koch (1979) investigated xenoliths present in the Bandelier Tuff. Although Precambrian xenoliths are rare in the tuff, 22 were found. In contrast to the cores from Fenton Hill, which are dominantly granitic, the xenoliths were roughly evenly divided between granitic and gabbroic rocks. The xenoliths were also typically more altered, sheared, and of a higher metamorphic grade than were the core samples. High-fluorine biotite and actinolite were common in the xenoliths as alteration products of original hornblende.

Phase II System Development and Investigations

After the technical feasibility of extracting geothermal energy from HDR was demonstrated in the Phase I system, drilling began on a pair of deeper holes for a larger Phase II engineering system. Drill holes EE-2 and EE-3 are inclined at a 35° angle and have true vertical depths of 4.39 km and 3.97 km respectively. The bottom-hole temperature of EE-2 is 323°C. Cores and cuttings from these wells indicate a continuation of the metamorphic complex observed in wells GT-2 and EE-1. Dikes of biotite granodiorite and monzogranite are intrusive into this complex. No single large homogeneous unit was observed in the deeper Precambrian section and, as a result, the Phase II system is much more heterogeneous than is the Phase I system. Cuttings analysis and structural analysis on cores suggested the possibility that several altered zones were intersected by the well bores.

Implications for Other Sites

The results of the deep drilling at Fenton Hill and subsequent fracturing and engineering tests can be used to evaluate the various exploration and assessment techniques. These evaluations have implications for the search for other HDR sites.

Although hydrologic disturbances resulted in erroneously high predictions of the geothermal gradient, the combination of field geology, geochronology, and gradient drilling was generally effective in identifying areas underlain by rock at elevated temperature. Additional hydrologic work would help in interpreting the results of gradient drilling.

Passive seismic techniques appear to be the most useful in evaluating reservoir permeability prior to drilling. Low seismic activity apparently fails to reopen fractures sealed as a result of high temperature and mineralizing fluids. Active seismic techniques were demonstrated to be useful in defining structures such as faults. Higher energy sources should be employed, however, to provide deeper penetration.

Permeable zones can also be identified using electrical or MT techniques. Although a thorough test was not performed because of financial constraints, preliminary results are encouraging.

Structural investigations, both surface and subsurface, can be valuable in predicting and interpreting the results of hydraulic fracturing. Low sun angle aerial photograph interpretation and joint analysis appear to be particularly useful. As much coring as possible should be done in future holes and techniques for orientation at high temperature should be developed. Much information was lost or confused because of the lack of orientation.

Petrologic investigations are fundamental in predicting the results of rock-water interactions along the hydraulic fractures. Complete mineralogical and chemical characterization is also important in predicting and interpreting fluid compositions.

From the results of the Fenton Hill drilling and the accompanying site investigation, the following HDR exploration and evaluation plan is proposed.

A Proposed HDR Exploration and Evaluation Plan

I. Identify areas of elevated subsurface temperature
   - Field geology
   - Volcanology
   - Geochronology
   - Geophysics
   - Gradient drilling

II. Evaluation of permeability
   - Passive seismic
   - LANDSAT and aerial photograph interpretation
   - Field geology
   - Active seismic
   - Electromagnetic

III. Prediction of hydraulic fracture behavior
   - Field and structural geology
   - Petrofabrics
   - Stress orientation

IV. Prediction of fluid chemistry
   - Petrology
   - Whole-rock geochemistry

References

Brookins, D. G., Forbes, R. B., Turner, D. L., Laughlin, A. W., and Naeser, C. W. (1977) Rb-Sr, K-Ar and fission-track geochronological studies of samples from LASL drill holes GT-1, GT-2 and EE-1, Los Alamos Scientific Laboratory report LA-6829-MS.

Brookins, D. G. and Laughlin, A. W. (1976) Isotopic evidence for local derivation of strontium in deep-seated, fracture-filling calcite from granitic rocks in drill hole GT-2, Los Alamos Scientific Laboratory dry hot rock program, Jour. Volc. and Geotherm. Res. v. 1, pp. 193-196.

Brookins, D. G. and Laughlin, A. W. (in press) Rb-Sr geochronological investigation of Precambrian samples from drill holes GT-1, GT-2, EE-1, and EE-2, Los Alamos Hot Dry Rock Program, Jour. Volc. and Geotherm. Res.

Charles, R. W. and Bayhurst, G. K. (in press) Rock-filled interactions in a temperature gradient: biotite granodiorite+H_2O, Jour. Volc. and Geotherm. Res.

Cordell, L. (1976) Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar, New Mexico Geol. Soc. Spec. Pub. No. 6, pp. 62-70.

Doell, R. R., Dalrymple, G. B., Smith, R. L., and Bailey, R. A. (1968) Paleomagnetism, potassium-argon ages and geology of rhyolites and associated rocks of Valles Caldera, New Mexico, Geol. Soc. America Memoir 116, pp. 211-248.

Eichelberger, J. C. and Koch, F. G. (1979) Lithic fragments in the Bandelier Tuff, Jemez Mountains, New Mexico, Jour. Volc. and Geotherm. Res. v. 5, pp. 115-134.

Hermance, J. F. (1979) Toward assessing the geothermal potential of the Jemez Mountains volcanic complex: a telluric-magnetotelluric survey, Los Alamos Scientific Laboratory report LA-7656-MS.

Jiracek, G. R. (1975) Deep electrical resistivity investigations coupled with dry geothermal reservoir experiments in New Mexico, Technical Progress Report to Nat. Sci. Foundation/RANN, Contract No. NSF G1-42835.

Kintzinger, P. R., Reynolds, C. B., West, F. G., and Suhr, G. (1978) Seismic reflections surveys near LASL geothermal site, Los Alamos Scientific Laboratory report LA-7228-MS.

Kintzinger, P. R. and West, F. G. (1976) Seismic reconnaissance of the Los Alamos Scientific Laboratory's dry hot rock geothermal project area, Los Alamos Scientific Laboratory report LA-6435-MS.

Laughlin, A. W. (1981) The geothermal system of the Jemez Mountains, New Mexico and its exploration, in Rybach, L. and Muffler, L. J. P. (eds.) Geothermal Systems: Principles and Case Histories, John Wiley and Sons, pp. 295-320.

Laughlin, A. W., Eddy, A. C., Laney, R., and Aldrich, M. J., Jr. (in press) Geology of the Fenton Hill, New Mexico hot dry rock site, Jour. Volc. and Geotherm. Res.

Robinson, E. S., Potter, R. M., McInteer, B. B., Rowley, J. C., Armstrong, D. E., and Mills, R. L. (1971) A preliminary study of the nuclear subterrene, Los Alamos Scientific Laboratory report LA-4547-MS.

Slemmons, D. B. (1975) Fault activity and seismicity near Los Alamos Scientific Laboratory geothermal test site, Jemez Mountains, New Mexico, Los Alamos Scientific Laboratory report LA-5911-MS.

Smith, R. L., Bailey, R. A., and Ross, C. S. (1970) Geologic map of the Jemez Mountains, New Mexico, U.S.G.S. Misc. Geol. Inv. Map I-571.

Turner, D. L. and Forbes, R. B. (1976) K-Ar studies in two deep basement drill holes: a new geologic estimate of argon blocking temperature for biotite (abs.), EOS Trans. Amer. Geophys. Un. v. 57, p. 352.

Zartman, R. E. (1979) U, Th, and Pb concentration and Pb isotopic composition of biotite granodiorite (sample 9527-2b) from LASL drill hole GT-2, Los Alamos Scientific Laboratory report, LA-7923-MS.

GEOPHYSICAL EXPLORATION FOR HOT DRY ROCK IN THE MIDCONTINENT

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The midcontinent of North America is commonly characterized as a stable cratonic area which has undergone only slow, broad vertical movements over the past several hundreds of millions of years. This is an unfertile area for hot dry rock (HDR) exploration, but recent geophysical and geological studies testify to the contemporary tectonism of limited areas within the midcontinent and the possibility of localized thermal anomalies, which may serve as sites for HDR exploration. HDR as an energy resource in the midcontinent is particularly appealing because of the high population density and the increasing demand on conventional energy sources.

Surface manifestations of potential midcontinent HDR sites are negligible, therefore geophysical techniques supplemented by deep drilling are necessary for HDR exploration. Within the past few years, gravity and magnetic data covering broad areas of the midcontinent have been observed, compiled, and in some cases filtered to enhance particular attributes of the anomaly fields. These maps and data are proving useful in mapping tectonic/lithologic regimes, which serve as guides to localize more detailed geophysical/geological studies. In addition, increasing availability of the results of deep drilling are providing new insight into the structure, geologic history, and geophysical parameters of the midcontinent - information which is critical to effective HDR exploration.

Five generalized models of exploration targets for midcontinent HDR sites have been identified: 1) radiogenic heat sources, 2) conductivity-enhanced normal geothermal gradients, 3) residual magmatic heat, 4) sub-upper crustal sources, and 5) hydrothermal-generated thermal gradients. These models are illustrated schematically in Fig. A-13.

Radiogenic heat sources localized in intrusives of sufficient volume and concentration of heat-producing radioisotopes are potentially viable HDR sites particularly where they are covered by a thermally insulating sedimentary rock blanket. Potential radiogenic heat sources include both felsic (e.g., Wolf River Batholith) and alkalic (e.g., Coldwell Complex) intrusives. Felsic intrusives are commonly characterized by gravity minima of the order of a few tens of milligals and negative magnetic anomalies. A typical example is the 1500 m.y. old granite pluton drilled over a vertical range of nearly 1 km in northern Illinois. Analyses of the core indicate an abnormally high U and Th content and a mean heat generation of roughly 40 x 10^{-13} cal/cm^3 sec. The three-dimensional configuration of this pluton has been determined by analysis of the associated gravity minimum and more poorly defined magnetic minimum. In contrast, recent studies in the midcontinent show that other felsic plutons are associated with relatively high magnetite contents resulting in strong localized magnetic anomalies. Available evidence suggests that the gravity signature of these high-magnetite felsic plutons is nil or slightly positive. Felsic plutons in the midcontinent are associated with Precambrian orogenic regimes (e.g., Penokean Foldbelt) as well as anorogenic areas (e.g., Central Province). Alkalic intrusives, which are marked by intense positive gravity and magnetic anomalies, occur with Proterozoic rifts (e.g., Coldwell Complex) and with major structurally disturbed zones (e.g., 38th Parallel Lineament).

An example of a potential radiogenic heat source in the basement of a cratonic basin associated with a gravity minimum has been investigated in the southeastern portion of the Michigan Basin. A residual Bouguer gravity of -25 mgals amplitude has been isolated over a portion of the Basin underlain by Grenville Province basement rocks. The gravity minimum is associated with a

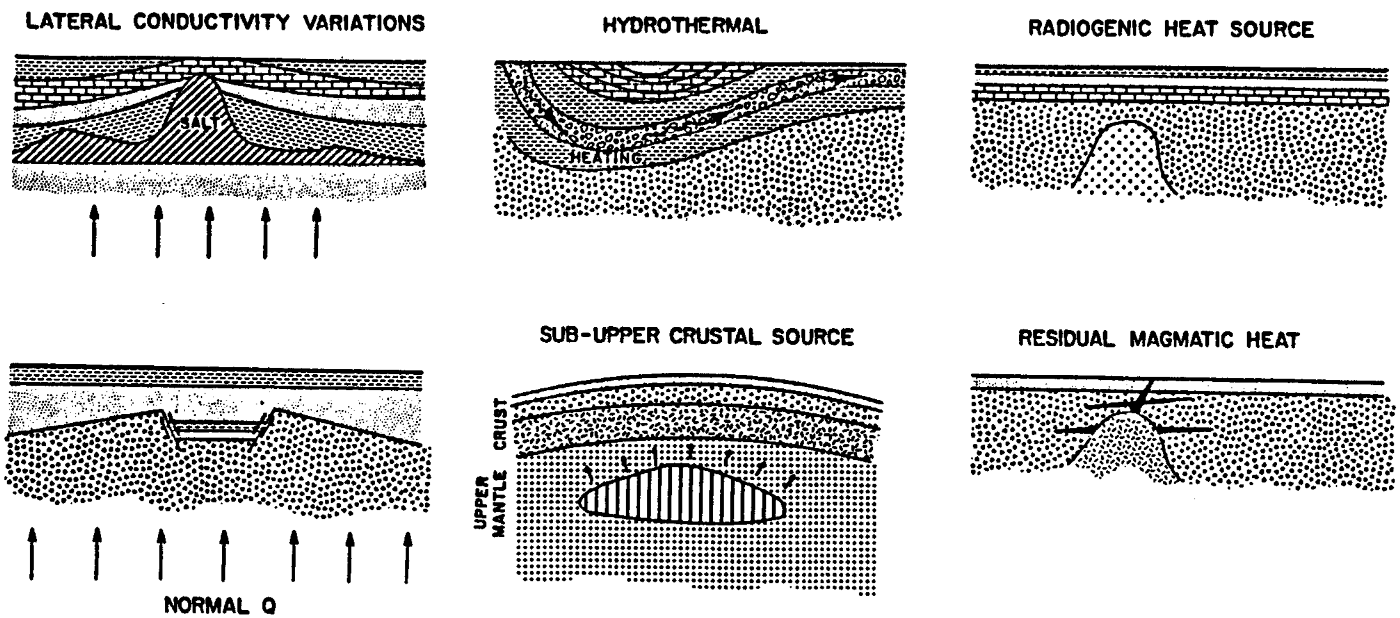

Fig. A-13.
Models of exploration targets for midcontinent HDR sites.

magnetic minimum ringed by a discontinuous positive anomaly. Geologic cross sections of the anomaly area prepared from well logs show that the gravity minimum cannot be due to increased thickness of evaporite deposits and evidence is lacking to explain the minimum with an increased thickness of low-density clastic sedimentary rocks. The thickness of low thermal conductivity shale within the basin over the basement anomaly source is approximately 400 m. The configuration of the hypothesized felsic source of the geophysical anomaly has been determined by modeling as an inverted cone, which is elliptical in horizontal cross section and reaches to a depth of roughly 8 km.

Channelling of heat through higher conductivity rocks can result in locally high geothermal gradients in a regionally normal heat flow field. Rock types that have significantly higher thermal conductivities with respect to the sedimentary rock overburden include evaporites and crystalline basement rocks. Thus salt diapirs (e.g., Gulf Coast Salt Domes), which are characterized by strong negative gravity anomalies, may perturb the local normal thermal gradients as will basement horsts and anticlines (e.g., Howell Anticline) within sedimentary basins. Basement uplifts are commonly, but not necessarily, associated with positive gravity and magnetic anomalies. Buried basement rifts and their related grabens (e.g., Reelfoot Rift) commonly involve marked relief of the basement crystalline rocks with the infilling sedimentary rocks. Thus abnormal thermal gradients caused by "channelling" are possible in the Mississippi Embayment, particularly near the head of the Embayment where geophysical/geological evidence indicate the presence of an ancient rift zone, which is undergoing recent tectonic activity (New Madrid Seismic Zone) as a result of the ambient stress field operating on this ancient zone of weakness. In a similar way, other Middle-to-Late Proterozoic rift zones, which occur extensively throughout the midcontinent, are of potential interest to HDR exploration. The geophysical signatures of these ancient rifts are varied depending upon the degree of crustal disruption and graben development, but generally the crust is thickened and linear trends of positive gravity and magnetic anomalies mark the location of mafic intrusive/extrusive rocks.

Potential residual magmatic heat sources include young (< 1 m.y.) upper crustal intrusions. Relatively small volume, anorogenic, alkalic intrusions are found within the Phanerozoic sedimentary rocks of the midcontinent along the 38th Parallel Lineament and the Gulf Coast region. Calculations indicate that these intrusives cool rapidly and thus would contribute no useful residual heat beyond 1 m.y. However, the youngest of these intrusions, which are manifested in positive gravity and magnetic anomalies, is approximately 70 m.y. Thus, residual magmatic heat is an unlikely source of HDR resources unless very recent intrusions can be located.

Sub-upper crustal sources involve anomalously high, lower crustal or upper mantle temperatures sustained for a sufficient period of time to cause surface thermal anomalies. Mass transport processes within the mantle, which lead to these temperature anomalies may be observed indirectly by the effect they have upon upper mantle and crustal structure and properties. Based upon geological/geophysical evidence, the Mississippi Embayment is the most commonly cited candidate in the midcontinent for relatively recent (Mesozoic) involvement in processes involving mass transport within the mantle. A long-wavelength magnetic minimum over the Embayment may be a result of an upwarp of the Curie point isotherm suggesting post-Mesozoic activity, but other explanations for the anomaly are plausible and recent analyses place the observed high heat flow in the Embayment under serious question.

Anomalously high local upper crustal temperatures in the midcontinent may be caused by heat transfer through ground-water movements caused by nonthermal induced convection. The prominent thermal anomaly in western Nebraska is believed to have this origin. Water heated in the lower reaches of the Denver Basin is driven upward in permeable horizons into the subsurface of the panhandle of Nebraska. The components which are required for the development of this type of thermal anomaly include structural attributes of sedimentary basins which are amenable to investigation by geophysical methods.

Consideration of the possible models for HDR exploration on sites in the midcontinent shows that geophysical techniques, particularly gravity and magnetic methods on a reconnaissance basis, are useful in delimiting localized areas for more detailed investigation and analysis.

SEISMIC METHODS OF HOT DRY ROCK EXPLORATION

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Seismic methods applied to hot dry rock exploration of the continental crystalline crust have had limited use but are potentially significant for both regional and local studies. Both active (seismic refraction and reflection profiling) and passive (local earthquake monitoring and teleseismic delay time studies) provide data on the velocity and attenuation structure of the crust which may be related to the thermal environment and potential hot dry rock resources.

Seismic techniques can be applied to hot dry rock exploration on a regional or a local scale. Regional studies are most useful for defining the structural framework, velocity and attenuation characteristics of the upper crust, depth to crystalline basement, stress determinations and possible correlations with temperature. Local studies may be useful for inferring composition, determining depth to basement, and mapping the configuration of potential hot dry rock volumes associated with plutons or other three-dimensional features.

Passive seismic techniques yield information on earthquake locations, and through focal mechanisms, on the prevailing regional stress pattern in the crystalline crust. Earthquakes are associated with hydrothermal anomalies in the tectonically active regions of western North America. In cratonic regions, zones of active seismicity are probably indicative of pre-existing geologic structures within the cystalline crust, which may serve to localize thermal anomalies. Focal mechanisms of earthquakes provide an important measurement of the regional stress pattern within the upper crust, which is important to the exploitation of hot dry rock resources. If earthquake monitoring is performed on a reasonably close station spacing, teleseismic delay time data may be used to infer seismic velocity anomalies at depth beneath an array of seismograph stations. Within tectonically active regions, these velocity anomalies are commonly related to thermal anomalies. Similar observations may apply to cratonic regions as well, although the expected anomaly due to velocity variations in cratonic regions is near the limit of resolution of the technique. The distribution of seismograph stations within cratonic regions is generally not adequate and additional studies will be required to demonstrate the utility of these techniques.

Laboratory studies of the seismic velocity of rocks consistently show that seismic velocity is inversely related to temperature. However, the effect is relatively small (on the order of -0.001 km/s/°C) and most thermal anomalies associated with hot dry rock volumes may be too small to show a velocity anomaly above the level of precision of seismic methods. In addition, other effects such as rock composition, porosity, and fluid content may produce large velocity differences. On a continent-wide basis for North America, both heat flow and inferred temperature at depth within the crust have been related to average seismic velocity properties. One study has shown a correlation between low Pn velocity (seismic velocity of the upper mantle) and high temperatures for data averaged by province. Heat flow is also approximately inversely proportional to crustal thickness, geologic age and average seismic velocity of the crust. Thus, seismic methods can be utilized to infer regional thermal characteristics as an aid to hot dry rock exploration.

Seismic refraction and reflection profiling techniques have considerable use in both regional and local hot dry rock exploration programs. Velocity structure of the upper crust may be an indicator of temperature and structural information such as depth to basement, presence of faults, locations of plutons and the thickness of plutons providing valuable information on potential heat sources.

Although seismic methods have good potential for utilization in hot dry rock exploration programs, both at a regional and local scale, and have been used successfully in several studies to date, the velocity effects and structural features which are expected to be associated with thermal anomalies are near the limit of resolution of available techniques. Thus, more detailed accurate and high resolution methods will generally be required for application of seismic techniques in hot dry rock exploration.

GEOTHERMAL ANOMALIES IN THE NORTHERN APPALACHIAN BASIN; WESTERN AND CENTRAL NEW YORK

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The known geothermal resources in the eastern U.S. are asociated with: (1) deep sedimentary basins with normal temperature gradients, (2) warm springs, (3) radiogenic granites covered by low thermal conductivity sedimentary rocks. Areas with a moderately thick sedimentary sequence underlain by radiogenic granite have great potential for hot dry rock geothermal application in the eastern U.S., whereas hydrothermal geothermal resources are associated with permeable stratigraphic layers in the deep sedimentary basins. Several areas in New York have been identified through previous investigations with the Los Alamos National Laboratory and New York State Energy Research Development Authority (NYSERDA) and are deemed to have good potential. In order to provide data to determine the geothermal character of this area, an integrated analysis of heat flow, bottom-hole temperatures (BHT), temperature gradients, geochemical indicators and gravity has been adapted. Detailed temperature-gradient analysis indicates that higher than normal geothermal gradients exist in New York; consistent patterns of high temperature gradients for areas near Cayuga Lake, East Aurora and Elmira were identified by using bottom-hole temperatures. Initial results suggested that the regional and local variations in temperature gradients were related to vertical and lateral conductivity changes and to local changes in heat flow due to heat generation in granitic plutons in the basement; this preliminary conclusion was consistent with the interpretation of heat flow on the Atlantic coastal plain by Costain. Due to the relatively simple geology, New York State provides an ideal location for the analysis of heat flow variation and relationship of this variation to basement lithology.

In March 1982 NYSERDA, in cooperation with the Department of Energy, completed drilling of a geothermal test well in Auburn, New York. This site is located within an area of anomalously high geothermal gradients determined from mean annual surface temperature and BHT. This well intersected marble in the Precambrian basement at 5100 feet and yielded a bottom-hole temperature of 51°C at 5260 feet about 12 hours after cessation of drilling. Hydrologic testing showed significant flows of water at greater than 50°C from 4750 feet in the Theresa Formation, a Cambrian dolomitic sandstone. Geophysical well logs suggest that water flow is from fracture permeability in this stratigraphic layer. The analysis of thermal conductivity, detailed temperature gradients, and permeability suggest that the elevated BHT-derived geothermal gradients in this area are caused by hydrothermal circulation along fractures in the stratigraphic section.

Similar results are indicated in other areas of the state; elevated gradients are often associated with observable faults and topographic linear features derived from interpretation of LANDSAT imagery. In light of this new data, the association of high geothermal gradients and regions underlain by radiogenic granites may be masked by structural effects in the stratigraphic layers. Many geothermal gradient anomalies in the Appalachian basin may be a result of hydrothermal circulation along faults and fractures and not entirely the result of conductive heat flow adjacent to radioactive granites.

GEOTHERMAL INVESTIGATIONS IN NEBRASKA

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Introduction

The geothermal regime of Nebraska was not known by any direct evidence prior to the commencement of a U.S. Department of Energy sponsored study in 1979. Although some interpretations of this geologic province indicated a typical midcontinent heat flow (Roy et al., 1972; Combs and Simmons, 1973; Lachenbruch and Sass, 1977), other studies suggested that anomalously high subsurface temperatures might exist in parts of the state (Swanberg and Morgan, 1979; Schoon and McGregor, 1974). The significance of these data and their relevance in the design of the geothermal resource assessment of Nebraska were discussed by Gosnold (1980). The resource assessment strategy included acquisition of heat flow data, temperature-gradient measurements in all available wells, an evaluation of the bottom-hole temperature data for more than 14,000 oil and gas wells, and preparation of a 5-mgal contour interval residual Bouguer gravity map. For reasons discussed elsewhere the bottom-hole temperature data from oil and gas wells are not particularly useful. However the other data excluding the gravity, map which is in preparation, have proved to be a successful approach to the resource assessment.

Heat Flow and Resource Assessment

Twenty-nine heat flow sites were selected throughout the state and included both the suspected anomalous and normal heat flow areas. Heat flow for most of Nebraska ranges from 40 mW/m^2 to 60 mW/m^2, but two laterally extensive areas (Fig. A-14) with heat flows as high as 120 mW/m^2 have been discovered (Gosnold et al., 1981). The high heat flow in the Nebraska panhandle appears to be due to slow, updip flow in deep aquifers in the Denver-Julesburg basin and corresponds to the eastern margin of the basin in Nebraska. Fig. A-15 illustrates how temperature gradients measured in eight

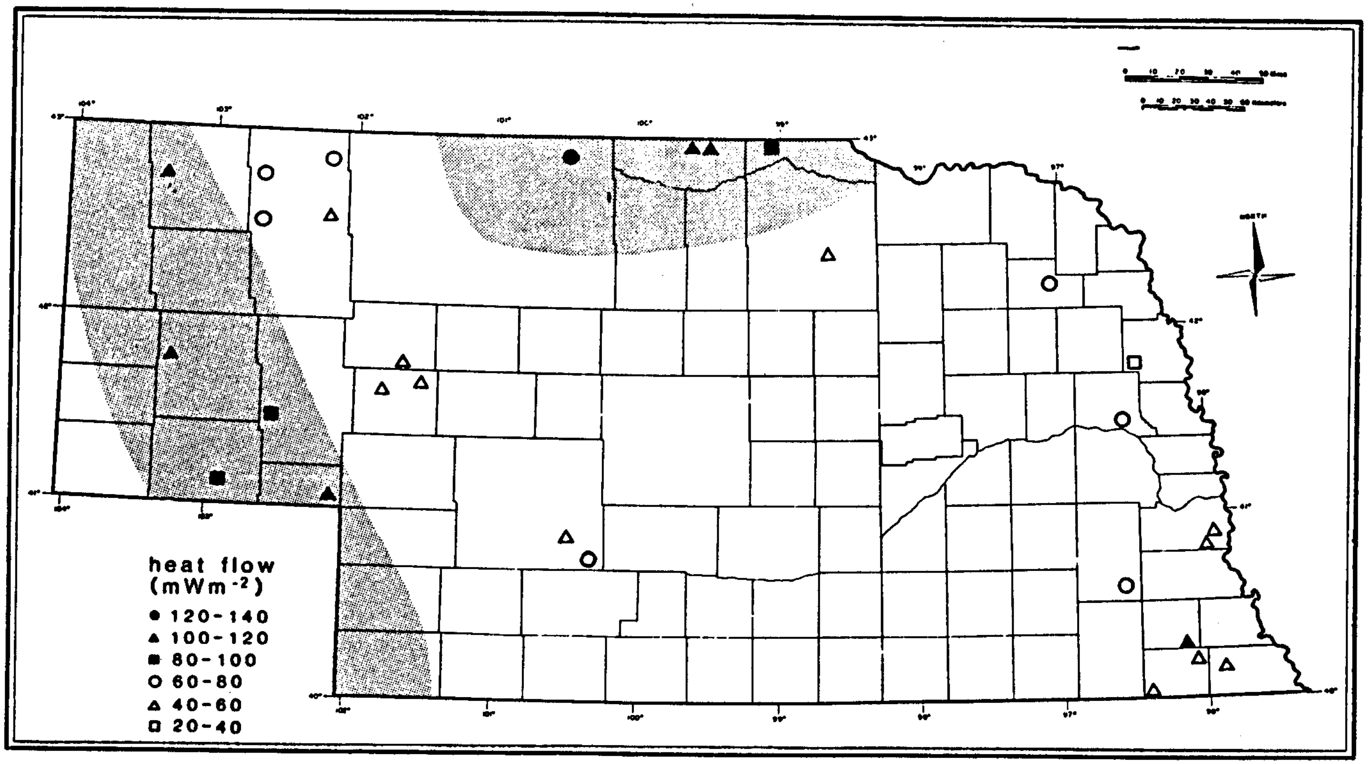

Fig. A-14.

Nebraska Heat Flow Data. High heat flow zones are shaded but the limits of the zones are inferred and are not certain. The high heat flow zone in western Nebraska may be due to updip flow toward the northeast from the Denver basin. The origin of the high heat flow zone in north-central Nebraska is discussed in the text.

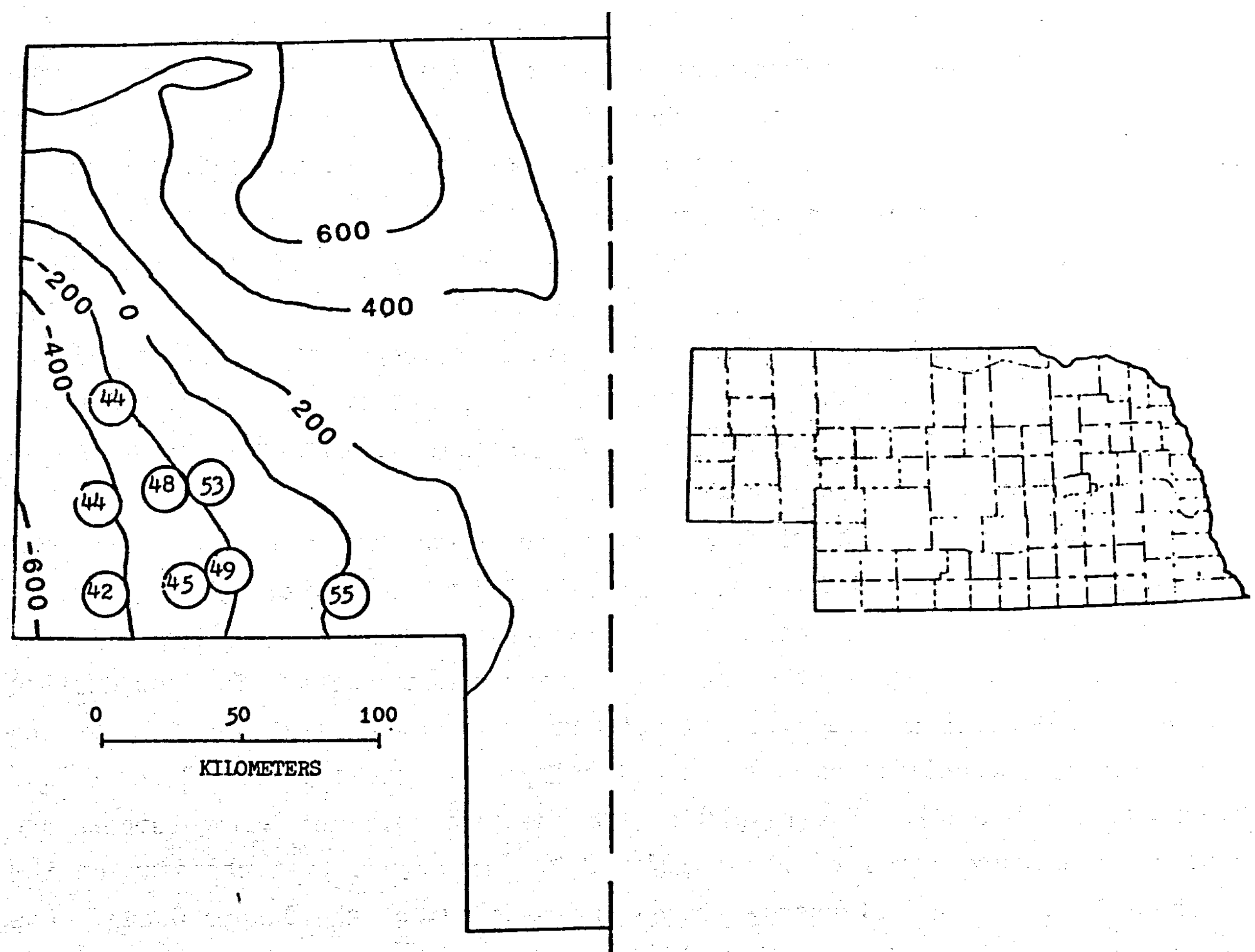

Fig. A-15.
Equilibrium temperature gradients for eight deep wells are given in the locating circles. Structure contours for the Dakota are given in meters with datum as mean sea level. The area of the enlarged map is shaded in the map above.

deep wells (1.2 to 1.8 km) relate to structure contours on top of the Dakota Group (Cretaceous). Modeling studies of the effects of updip water flow within the lower sand units of the Dakota Group suggest that a flow rate of about 0.4 to 0.6 m/yr could produce the subsurface temperatures observed above that horizon.

The high heat flow in north-central Nebraska is not easy to explain. Four heat flow sites in the area range from 100 mW/m^2 to 140 mW/m^2, and temperature gradients logged in 14 deep water wells range from 50 K/km to 90 K/km. Updip water flow is an unlikely explanation for the high heat flow because the sediments dip at very shallow angles. A more likely explanation is that upward flow along fractures enters aquifers such as the Dakota Group and flows laterally, causing the high heat flow. A third possibility is that the Precambrian basement rocks contain high amounts of uranium and thorium and have high heat generation values. We have no firm data as yet that could help in the interpretation of this region. However, by midsummer of 1982 we expect to obtain a temperature log in a recently completed heat flow hole that bottoms in Precambrian granite. The hole has been logged to a depth of 530 m, which reaches upper Paleozoic Carbonates, and the temperature log gives no indication of hydrologic disturbances. At present we can only speculate on the source of heat in this region.

We have obtained equilibrium temperature measurements in more than 100 additional wells; and, we have combined this information with heat flow data, thermal conductivity data, and stratigraphic data from electric logs of deep wells. These data were synthesized with the assumption that, in a conductive thermal regime, subsurface temperatures are determined by the heat flow and the thermal conductivities of the lithologic units present (Gosnold and Eversoll, 1981; 1982). The result is the identification of a low-temperature geothermal resource area of about 107,000 km^2 in extent that contains on the order of 1000×10^{18} J of energy stored in the sands of the Dakota Group. One of the primary reasons for the existence of this low-temperature geothermal resource is that most of the stratigraphic section overlying the Dakota Group in Nebraska consists of shales that have thermal conductivities of around 1.1 W/m/K. Consequently the geothermal gradients within these thick (up to 2 km) shale sections are approximately 50 K/km even where the heat flow is not anomalously high (Fig. A-16).

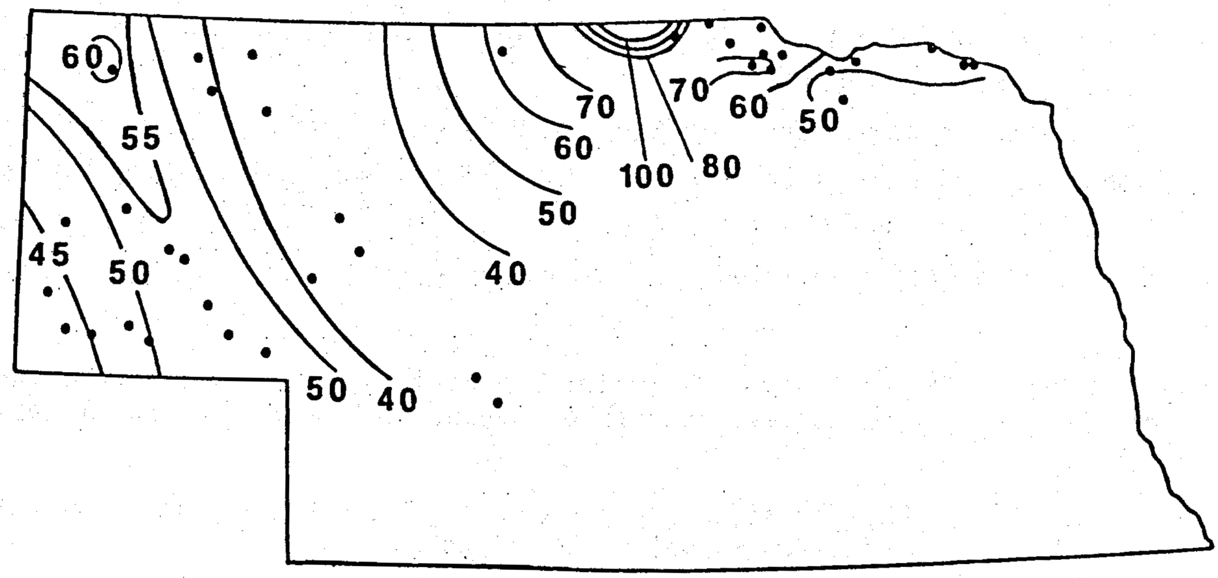

Fig. A-16.
Geothermal gradients from equilibrium temperature logs.

Hot Dry Rock Prospects

Extension of the present data to deeper regions in search of higher temperatures becomes mostly speculation. We have very little information on the amount of radioactive heat generation in the Precambrian basement rocks, but we are attempting to interpret what is available. Small samples of drill cuttings and some few core samples of basement rocks have been recovered during the drilling of deep, mineral-exploration holes. German (unpublished Masters Thesis) used fission track mapping techniques to investigate the nature of uranium occurrences in these samples. In general he has found that in several instances the amount of uranium contained in secondary minerals equals or exceeds the total uranium in primary minerals in these samples. It has been suggested (Gosnold, 1976; 1978; Gosnold and Swanberg, 1980) that uranium in secondary minerals in intrusive rocks represents enrichment in uranium that occurred during interaction between the rocks and convecting meteoric ground water. We are investigating the possibility that the fission track data may give some indication of heat generation in the basement rocks. If this method of study proves to be valid it could be useful in estimating upper crustal temperatures in regions with covered basement rocks. It should be pointed out that the basement samples we have are too small for gamma-ray spectrometric determination of heat generation and are not available for destructive chemical analyses.

Calculations of temperatures in the basement rocks based on basement heat generation values ranging from 5 to 15 HGU indicate that drilling depths on the order of 5 km are to reach the 200° isotherm. In western Nebraska up to 3 km of this drilling depth would be in sedimentary rocks.

References

Combs, J., and G. Simmons, 1973, Terrestrial heat flow determinations in the North Central United States, Journal of Geophysical Research, v. 78, pp. 441-461.

German, K.E., Jr., 1982, The secondary enrichment of the Precambrian basement rock of Nebraska, M.S. Thesis, University of Nebraska-Lincoln.

Gosnold, W.D., Jr., 1976 A model for uranium and thorium assimilation by crystallizing magmas and cooling plutons through interaction with meteoric ground water and other crustal fluids, Ph.D. Dissertation, Southern Methodist University, 141 pp.

Gosnold, W.D., Jr., 1978, A hypothesis to explain the vertical distribution of heat production in the continental crust, EOS, v. 60, p. 392.

Gosnold, W.D., Jr., 1980, Preliminary report on the geothermal resource potential of Nebraska, Geothermal Resources Council Transactions, v. 4, pp. 45-48.

Gosnold, W.D., Jr., and C.A. Swanberg, 1980, A kink in the vertical distribution of heat generation in the continental crust, EOS, v. 61, p. 1193.

Gosnold, W.D., Jr. and D.A. Eversoll, 1981, Usefulness of heat flow data in regional assessment of low-temperature geothermal resources with special reference to Nebraska, Geothermal Resources Council Transactions, v. 5, pp. 79-82.

Gosnold, W.D., Jr., D.J. Becker, and D.A. Eversoll, 1981, New heat flow data from Nebraska, EOS, v. 62, p. 1064.

Gosnold, W.D., Jr., and D.A. Eversoll, 1982, Geothermal resources of Nebraska, 1:500,000 scale map, National Geophysical and Solar-Terrestrial Data Center, National Oceanic and Atmospheric Administration, Boulder, Colorado.

Lachenbruch, A.H., and J.A. Sass, 1977, Heat flow in the United States and the thermal regime of the crust, In The Earth's Crust, edited by J.G. Heacock, American Geophysical Union Monograph 20, pp. 626-675.

Roy, R.F., D.D. Blackwell, and E.R. Decker, 1972, Continental heat flow In Nature of The Solid Earth, edited by E.C. Robertson, McGraw Hill, New York.

Schoon, R.A., and D.J. McGregor, 1974, Geothermal potentials in South Dakota, South Dakota Geological Survey Report of Investigations, 110, 76 pp.

Swanberg, C.A., and P. Morgan, 1979, The linear relation between temperatures based on the silica content of ground water and regional heat flow, Pure and Applied Geophysics, v. 117, pp. 227-241.

GEOTHERMAL EXPLORATION IN THE RHINE GRABEN
(West Germany and France)

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The Rhine graben (Fig. A-17), situated in southwestern Germany and northeastern France, has been and is the main target for geothermal exploration in Germany. This is mainly due to the fact that some wells being drilled for oil exploration encountered anomalous high temperatures (up to 160°C in 1800-m depth). Prior to these observations, high geothermal gradients were known in the oil mining region of Pechelbronn. Numerous hot springs in the surroundings of the graben indicate active hydrothermal convection. In 1975, the commission of the European Communities started a research and development program for geothermal energy. This program concentrated on exploration in special regions, assessment of geothermal potential of the states of the European Communities, data gathering and feasibility studies. The research work in the Rhine graben was performed in cooperation with universities, regional geological surveys and other institutions.

In order to have a better view of this exploration campaign, it is necessary to summarize some facts on geology and geophysics of the Rhine graben. The hercynian basement consists of gneisses and metamorphic schists intruded by granites of carboniferous age. The Permian is developed in some regions as a thick sequence of conglomerates, arkoses and siltstones. The Lower Triassic formed by the Buntsandstein, a sandstone with its thickness increasing from south (30 m) to north (500 m). The Middle and Upper Triassic plus the Jurassic is a series of marls, limestones, and sandstones, up to 500-m thickness. In the Uppermost Jurassic sedimentation stopped, and began again in a bigger scale only in the Rhine graben since Middle Eocene. A 2,000-3,000-m-thick sequence of mostly marls, clays and evaporites was deposited in the period ending with the Upper Miocene. In the Pliocene, the tectonic style changed froom an extensional rift valley with mainly vertical movements to left-lateral strike slip tectonics continuing till today, as can be concluded from fault plane solutions of earthquakes.

The most prominent geophysical feature of the Rhine graben is the updoming of the mantle under its southern part up to 25-km depth. The absence of a

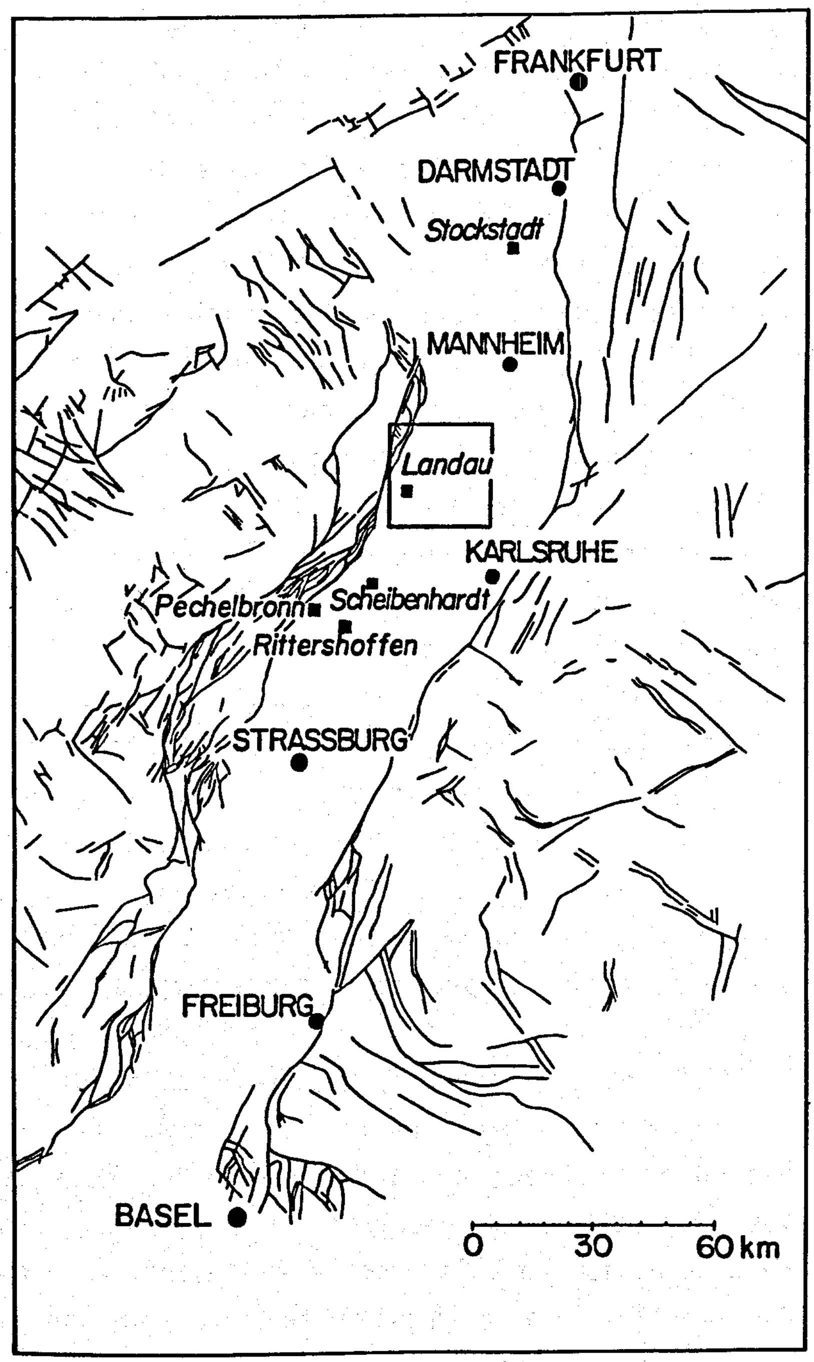

Fig. A-17.
Sketch map of the Rhine graben with locations mentioned in text.

corresponding positive Bouguer anomaly is believed to indicate hot low-density material under the graben. However, the surface heat flow is quite normal; 70 mw m^{-2} has been measured in potash mines of the southern Rhine graben. Values twice as much as this one have been obtained from some oil wells in the oil fields of Pechelbronn and Landau, but exploratory wells drilled only a few kilometers away from such "hot spots" encountered normal and low temperatures. This is in good agreement with observations on the degree of coalification of organic matter, which is dependent on the temperature history of that material in cores from many boreholes and clearly shows that almost no connection exists between the recent temperature field and the coalification. In now "cool" boreholes the degree of coalification may be high indicating high temperatures in the past, or in some "hot" boreholes there is no corresponding coalification. Thus, the temperature field, varying considerably in space and time, may be best explained by convective heat transfer, i.e., deep ground-water circulation. Two-dimensional numerical modeling of the temperature effect of hydrothermal convection yields a minimum age of the geothermal anomalies of about 80,000 years, under the assumption that water rises from 6-km depth with an initial, undisturbed temperature gradient of 30°C/km. It is assumed in this model that the water rises vertically in the basement and flows horizontally in the strata of the Buntsandstein (Fig. A-18). The permeability in the basement that is necessary for the required flow (1.2 Mg cm^{-1} $year^{-1}$) is due to the regional shearing parallel to the graben axis, opening up second-order shear planes or Riedel shears, which can be seen in quarries on the shoulders of the graben and even in the sedimentary graben fill. The geothermal anomalies are bound to tectonic horse structures within the graben, which is probably caused by the hydraulics of the convection system.

Geophysical field experiments and measurements giving information about the underground temperatures were performed extensively in the sixties and seventies, including refraction and reflection seismics, gravimetry, magnetotellurics, magnetics, and geoelectrics. The main result of all this work, of interest here, is the existence of a temperature anomaly in the lower crust and upper mantle associated with the diapiric uprise of the mantle mentioned above. The northern part of the graben with its near-surface anomalies was not investigated in detail in its deep structure. However, some exploration work has been done successfully on the known geothermal anomalies, mainly for testing the methods (magnetotellurics, magnetic deep sounding and microseismic noise). Special exploration for exploitation projects has been carried out by reflection seismics (Vibroseis), looking for deep hot aquifers in the Triassic and Jurassic formations of the graben.

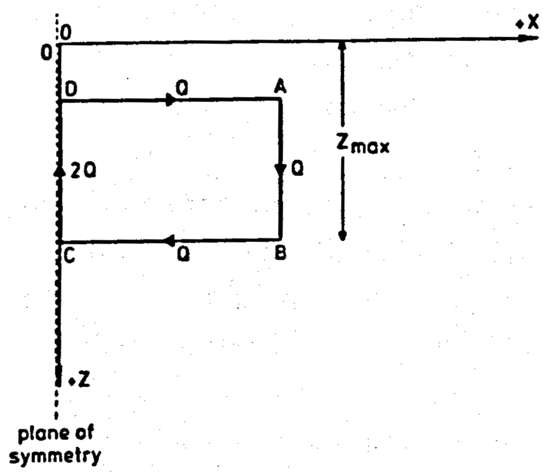

Fig. A-18.
Vertical section used for calculation of temperature effects of hydrothermal convection. Water is entering the system at Point A and is then flowing according to lines with arrows.

PARAMETRIC EXPLORATION FOR HOT DRY ROCK

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Panaceas will elude the Hot Dry Rock explorationist as they have the hydrothermal reservoir hunter. No single technique can determine the petrophysical and temperature regime of rocks at depth. Principles and limitations of individual techniques define the uncertainty associated with each. Joint- or multiple-parameters may narrow down uncertainties.

Heat flow techniques increase in reliability with the increase in spatial data distribution and depth of holes. Spatially distributed data permits the separation of effects due to shallow convective regime from deeper heat sources, convective or conductive. Structural geology, stratigraphy and hydrogeological data may provide useful constraints to heat flow models.

Electrical resistivity methods can determine the gross three-dimensional distribution of the conductivity of the rock volume. That conductivity value can be affected by, or be the composite effect of temperature, porosity, saturation, presence of metallic minerals, salinity of the saturating fluid and geometrical effects.

Seismic techniques permit the 3-D determination of compressional and shear wave velocities, their ratio and their distinct attenuation rates. Compressional wave velocity is affected by the rock mineralogy, porosity, pore fluid, compressive modules, and temperature. Shear wave velocity is affected by the same parameters as compressional waves, but in a different way than compressional waves. Hence, changes in the ratio of P/S wave velocity (or Poisson's Ratio) can serve as important indicators of changes in rock temperature, pore fluid state and degree of saturation, and pore geometry.

Gravity and magnetics provide valuable structural and generalized stratigraphic distribution of rock masses that are important in the determination of gross geometrical character of the geological regime at a specific site. The drastic change in density at the melting point provides ways of determining the approximate geometry of the molten rock mass, and thus provides at least one temperature-depth plane information. The Curie point, at which rocks lose their magnetism due to temperature (about 578°C), permits the mapping of another temperature plane. Neither the gravity method nor the iso-Curie technique can guarantee unique interpretations. However, the gravity method is less subject to the ambiguities that shroud magnetics, inasmuch as magnetic susceptibility effects, remanent magnetization effects, hydrothermal oxidation of magnetics can all drastically affect the magnetic field in a way that may not be easily distinguishable from the Curie effect.

Regional geological studies provide initial conceptual models on the nature and distribution of various rock types. The reasonableness of assumptions regarding the occurrence of a suitable heat source, rock environment of the desired permeability characteristics may be adjusted based upon such preliminary studies, especially when supported by age dating, mapping and analysis of the geochemistry of water and gases of local springs.

Success of the technology of geothermal (hydrothermal or Hot Dry Rock) resides in the synergism of multi-technique approach to the definition of in-site geothermal and petrophysical properties. The nonunique relationships between any one geophysical technique and the desired temperature or petrophysical state of the rock would foredoom any attempt in prognostication. Inchoate success in reducing temperature, porosity and other desired information may come about through joint- or multi-parameter interpretation of different physical rock properties. These include joint gravity and magnetic data, electrical resistivity and seismic data, compressional and shear wave velocity data, seismic wave attenuation, as related to shear and compressional wave velocity data, and other data set permutations. Even when data sets are limited for a given area, the stratigraphic changes in one single variable may provide an important insight to significant changes in the pore volume character (or some other character). This was the case for the "bright spot" technique in seismic reflection or oil, where the slight change in acoustic impedance due to saturation with oil or gas, as distinct from water, made it possible to detect the petroleum deposit directly, in some cases.

An underutilized body of data, often already in the files of the exploration company, may include the following:

(1) Interval velocities and their areal distribution. These are calculable in every case where coherent reflectors occur and sufficiently large cable spreads have been employed in taking the data.
(2) Poisson's Ratio areal distribution.
(3) Changes in Poisson's Ratio and attenuation as related to porosity and pore fluid characteristics.
(4) Reinterpretation of electrical resistivity data, by using seismic stratigraphy to provide modeling constraints.
(5) Isolation of preferred fracture patterns in rocks from data on electrical and seismic wave anisotropies.

Joint multi-technique interpretations, associated with a more quantitative assessment of the causes of relative magnitude changes in each of the parameters, offer the promise of a greater success rate in predicting the petrothermal or hydrothermal state of the rocks. A few examples to demonstrate this statement, culled from various case histories, will be shown to demonstrate the proposed concepts.

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